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A Publication of the Society of Economic Paleontologists and Mineralogists
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AUGUST, 1933

THE SULFUR CYCLE IN SEDIMENTS

E. WAYNE GALLIHER
Stanford University, California

ABSTRACT

The origin and transformation of sulfur in sediments is considered from the geobiological point of view. The general sulfur cycle is outlined, and the part some of the organisms may play in the formation of petroleum is suggested. The relation between the quantity of organic matter and ferrous sulfide in a sediment is shown. Emphasis is laid on the fact that the black mud accumulates under alkaline conditions.

The brown iron-containing layer which overlies the black sediments is the habitat of a group of organisms which probably play a very important part in the formation of ocherous concretions.

IMPORTANCE OF THE PROBLEM

Hydrotroilite is an amorphous, hydrous sulfide of iron. It may probably be a hydrophyllic colloid; that is, a minute particle over the surface of which is held, by adsorption, a mantle of water. The formula of hydrotroilite is generally expressed as FeS_x $(H_2O)_y$. It is defined here at the outset because it is so essential to, and occupies a key position in, the sulfur cycle in sediments.

The distribution of this mineral in Recent sediments has considerable geological significance. In one case it may be the progenitor of marcasite or pyrite (see 31,[1] and 12, pp. 267-269). In another case it can represent the first stage in the formation of the commonly encountered hydrous and anhydrous ferric oxides. The series of reactions in which hydrotroilite becomes involved depend, of course, on the environment of a sediment at the time of its deposition, as well as its subsequent history.

Furthermore, apart from its giving an indication of the geologic history, or more particularly the geochemical history, of a sediment, hydrotroilite is one of the products which may be involved in a process of intense geologic interest—that of oil formation. The reactions connected with the sulfur cycle afford a means whereby postulates may be advanced regarding oil genesis.

[1] These numbers refer to the bibliography compiled at the end of the article.

THE SULFUR CYCLE

The General Scheme of the Cycle.—The detailed study of the mechanism of the sulfur cycle lies in the province of bacteriology, but in order to understand the facts obtained from the analysis of sediments it is necessary to present a summary of the scheme as it is now understood. Such a brief account omits much that pertains to the metabolism of the organisms involved, but the details necessary for the geological interpretation are included.

In figure 1 a rough idea of the steps of the cycle is diagrammed. The steps which lead to the formation of black mud—that is, hydrotroilite-containing mud—or sand are emphasized. The processes outlined there may be described in a manner something like this: formed. Finally, these animal proteins may also be consumed in the metabolism of bacteria. These bacteria which depend for their energy supply upon organic or carbonaceous matter such as the plant and animal proteins are called *heterotrophic bacteria* (37, p. 408). And while they are decomposing the organic proteins, considerable hydrogen sulfide is generally set free.

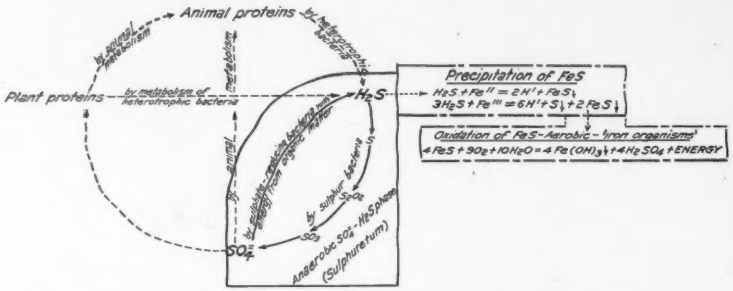


FIG. 1. Schematic diagram of the natural sulfur cycle, with special regard to the reactions which are involved in the formation of ferrous sulfide sediments. Reactions are also given which relate to the oxidation of ferrous to ferric iron. The latter is found in the brown layer overlying the sulfide-bearing muds.

Plants build themselves by photosynthesis. They are organic compounds and, as such, serve as the ultimate source of energy for nearly all bacteria. The special groups of bacteria which do not use organic matter for energy are those which have the power of utilizing the energy released when inorganic compounds oxidize. They are called *autotrophic* bacteria and play an especially important part in some parts of the cycle as, for instance, in that part called the "sulphuretum."

In the proteins of the plant compounds sulfur is the element of chief concern. These proteins may be consumed by bacterial activity and the sulfur transformed into a different chemical set-up; or they may be converted into animal proteins when the plants are eaten, and again the sulfur is trans-

But hydrogen sulfide, and sulfur as well, are supplied also by the reduction of sulfates. They are formed during the metabolism of the sulfate-reducing bacteria, and their formation marks one of the major steps in the cycle.

It is clear, then, that at least three kinds of micro-organisms play parts in the sulfur cycle, viz.: the autotrophic bacteria, such as those oxidizing sulfur from sulfide to sulfate in the "sulphuretum"; the sulfate-reducing bacteria which need sulfur in their metabolism and to get it reduce sulfate to sulfide even though it requires considerable energy expense; and the very important group of heterotrophic bacteria which utilize organic compounds and

liberate hydrogen sulfide, among other things, during the decomposition of some of the proteins.

From the point where hydrogen sulfide is formed the reactions may proceed in different ways. They become principally nonorganic reactions, if the term may be allowed. By double decomposition, the hydrogen sulfide and any soluble ferrous salts that are present will precipitate ferrous sulfide; thus hydrotroilite is formed. Or, the hydrogen sulfide may reduce any ferric iron that is present to ferrous iron, and the reaction above may repeat to form hydrotroilite; the ferric to ferrous transformation is accompanied by the oxidation of some sulfide to free sulfur, and this in turn is susceptible to further oxidation. All these detailed interchanges depend upon the immediate environment in which the bacteria live, and some details of this milieu will be considered next. For other explanations of the sulfur cycle, references 4, 10, and 21 are admirable.

Some Details of the Cycle.—The most important link of the sulfur scheme for consideration here is that designated in figure 1 as the anaerobic sulfate-hydrogen sulfide phase. It is important not only because it is the key to the formation of hydrotroilite under many conditions, but also because the activities of the organisms involved (the sulfate-reducing bacteria) may be intimately connected with the formation of petroleum. The field lies uninvestigated, but Thayer (34, p. 453) has suggested that:

> in the presence of sufficient sulfate, the sulfate-reducing bacteria may be able to reduce the fatty acids, and indeed other organic matter; and finally, that the anaerobic decomposition of the pigments (of diatoms), which are largely hydrocarbon in nature, may lead to the formation of petroleum-like compounds.

In this sulfuretum the micro-organisms that are associated together include at least five kinds which are enumerated here:

(1) The sulfide bacteria which obtain their energy primarily from the oxidation of hydrogen sulfide and other sulfides. The thread-forming, purple, and other bacteria which accumulate sulfur within their cells are included here. (2) The thiosulfate or thionic acid bacteria which get their energy from the oxidation of thiosulfates. (3) The sulfur bacteria which use the oxidation of elementary sulfur for energy source. (4) Two associated organisms; one oxidizes the sulfur to hyposulfite (S_2O_2); the other oxidizes the hyposulfite to sulfate (SO_3). They require energy from organic acids, carbohydrates, or amino acids. The rate at which they work depends upon the nature of their carbon source. (5) Bacteria capable of reducing sulfates and other oxygen-rich sulfur compounds (like thiosulfates) to H_2S. They are strictly anaerobic, deposit sulfur in the colony and among the cells (due to incomplete reduction of the sulfate), have the ability to utilize the sulfates and thiosulfates as sources of energy and carbon, and require the presence of essential inorganic elements in available forms (see 37, pp. 188-609, *passim*).

The first three of these groups are autotrophic; that is, they are capable of using the energy liberated by inor-

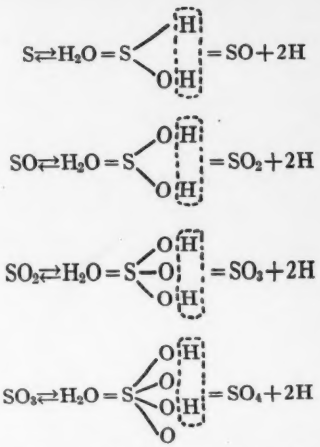
ganic chemical processes. The last two groups obtain their energy from carbonaceous substances and, hence, are called heterotrophic.

The black-mud community includes these various types of organisms and it has been ingeniously called the "sulphuretum" (4, p. 614), or sulfuretum. In the present paper the term is used to designate this locale in which the important sulfate-to-hydrogen sulfide-to-sulfate cycle takes place.

The sulfuretum is an anaerobic environment. Yet the change from elementary sulfur to sulfate is an oxidation and is carried out there. This apparent anomaly is explained by the fact that oxidation is the equivalent of dehydrogenation; that is, the binding of an atom of oxygen to a compound is the same as removing two atoms of hydrogen, either directly or by a series of steps. Something, however, must accept the hydrogen. The idea is expressed clearly by Waksman (37, p. 520):

> processes of oxidation can . . . be considered either as (1) aerobic processes, in which atmospheric oxygen acts as the hydrogen acceptor or . . . oxidizing agent and (2) anaerobic processes, in which organic or inorganic compounds act as the hydrogen acceptors, both processes resulting in the liberation of energy.

This mechanism of dehydrogenation as applied to sulfur is really fairly simple, and is shown in the following steps. In each the essential idea is that the primary element or compound given at the beginning of each step is first hydrolized and then hydrogen is taken away. Thus an oxidation is consummated:



In the sulfuretum the compounds which act as hydrogen acceptors may be varied: they may be carbon compounds, and the typical fermentation processes belong in this type of reaction; the nitrates may act as acceptors —it is clear that the reduction of nitrate to ammonia involves the acquisition of hydrogen; or the reduction of sulfates is a hydrogen-acceptance reaction. The reduction of sulfate (SO_4) to hydrogen sulfide (H_2S) is an especially good example of this reaction.

Now, again, the dehydrogenation is the equivalent of oxidation and to say that organic compounds are dehydrogenated is the same as saying that carbon compounds are oxidized. Oxidation liberates energy; reduction requires energy. Thus the reduction of sulfate to hydrogen sulfide requires energy.

But the bacteria of group five mentioned above are able to take advantage of the energy expended when the carbon compounds are oxidized (or dehydrogenated) and use it to reduce sulfates. Stated in other words, there is

involved a larger liberation of energy by dehydrogenation (oxidation) of carbonaceous substances than is required in the change of sulfate to hydrogen sulfide.

Other things being equal, the cycle of sulfate-to-sulfide-to-sulfate continues, then, as long as organic matter is present and as long as sulfate is available for these sulfate-reducing organisms to use in their metabolic processes. Sea water offers a practically unlimited supply of sulfate, and the development of black mud in marine basins should then depend on the availability of carbonaceous detritus.

With the course of the cycle outlined, certain facts relating to the specific chemical environment of these organisms in the sediment may be pointed out. Details of the organisms and the reactions they are instrumental in carrying out may be found in references 3, 4, 17-20, and 37.

THE BLACK MUD MILIEU

Relation of Organic Matter and Sulfide—From the above considerations it is evident that the sulfate-sulfide phase of the major cycle is largely dependent on organic matter for its activity. It is possible to show this correlation between the organic content of black muds and their ferrous sulfide content. The muds analyzed were all collected in Monterey Bay, California, and have been summarily reported on elsewhere (see 13). They were all collected with a tube sampler and analyzed when fresh.

Ferrous sulfide is taken to represent an index of the accumulation of sulfide. It is assumed that enough iron is present in the sediments to react with the hydrogen sulfide generated. It is impossible in a short time to determine all the complex organic compounds present in the samples; therefore total organic carbon is used as an index of total organic matter.

The maximum black coloration encountered in the Monterey Bay sediments nearly always lies within 1.5 to 2 centimeters below the overlying brown layer. The black coloring is due, of course, to the iron sulfide, while the overlying brown area is its oxidation product—ferric oxide, always hydrous. This blackest area also represents the maximum in the vertical distribution of organic matter in the mud. So in order to compare directly, both ferrous sulfide and organic matter are determined in the same spot in the sample.

The factors which determine the depth at which one should encounter the line between the black area and the overlying brown layer probably include the disturbance to which the sediment has been subjected, the porosity of the material, the rate of supply of organic food falling on the floor of the basin, and the oxygen tension of the overlying water.

In the samples from Monterey Bay the iron oxide layer never extends to the same depth in any two samples, and even in a single core the range is often of the order of 2 to 5 centimeters.

The table on page 56 gives the analytical data. It is shown graphically in figure 2. The station numbers refer to those shown on the map in the report cited above (13).

In some cases (samples 67-B, 14, 16, 119), the iron is greater than the

Station	Depth of water Meters	Depth in mud Centimeters	S Per cent	Fe Per cent	Organic Carbon Per cent
67-D	0.0	5	0.8	1.3	5.2
67-B	0.5	4	0.2	0.4	2.1
16	37	5	0.4	0.8	0.9
14	42	3	0.5	0.9	1.0
90	88	2	0.2	0.3	0.8
34	105	2	0.2	0.3	0.6
103	265	3	0.8	0.9	1.9
103	265	6	0.2	0.4	0.8
131	492	5	0.2	.....	0.6
119	750	4	0.1	0.2	0.6

amount needed to satisfy the formula, FeS; in the others, less. Since the iron determinations are accurate only within 0.1 per cent, and since there is some solution of iron silicate minerals during the determination, it is difficult to show more than a rough correlation of FeS and organic carbon.

It is clear that there is a decrease in carbon and sulfide contents of the muds with increase of depth of sample, although the relation is only approximate. However, this general conclusion is justified by contrasting the intense black muds of the shallower regions of the Bay (0-40 meters) with the blue-gray muds of the greater depths (700-800 meters).

The correlation of the darker color with the greater sulfide content may be observed in the field with nearly every dredging. Its relation to the organic matter in the muds, and their position with respect to the shore-line may be used in a rational consideration of what is to be expected in practically any basin of deposition.

The major amount of organic detritus is assimilated by micro-organisms, either floating or dwelling in the sedi-

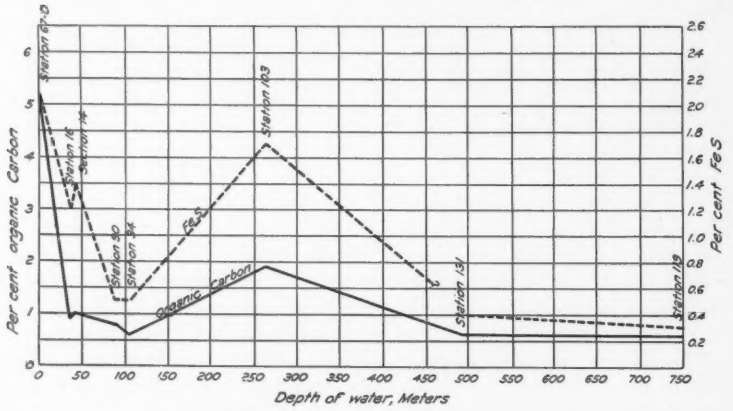


FIG. 2. Graph of data showing the variation in amounts of organic matter and ferrous sulfide in samples of sediments from Monterey Bay, California. Organic carbon is used as the index of total organic matter.

ments, before it is transported far from the land or settles to any great depth (8, p. 243; 28, pp. 365-386; 29, pp. 253, 411; 5, p. 503). The localized areas where dead plankton accumulates might occur under conditions of relatively quiet, shallow water; this, of course, may be found at nearly any depth depending on the submarine topography. There are also the localized areas where larger organisms have been killed; there is thus a temporary accumulation of much organic matter in small, sporadically located areas. Probably these two exceptions are the only ones that might be said to disprove the generalization that organic carbon, and consequently iron sulfide, decreases with the increase in depth of water.

Another factor besides available organic matter which bears a relation to sulfide formation is bottom temperatures. Sulfate reducers withstand temperatures of 0° C to 80° C. At the lower temperatures, such as 4° and 5° encountered in the deep stations of the list given above, the *rate* at which sulfide is formed is retarded. But there is no reason for assuming that the *amount* of sulfide is less there, given an equal quantity of organic matter. Certainly there is almost an unlimited time for the process to operate, and we may consider the sulfide content of a given mud as probably the maximum for that depth, with that content of organic matter.

Comparison With Other Basins.— These data pertaining to the organic matter and the sulfide in the muds of Monterey Bay are of little value unless compared with data from other basins. Comparisons are difficult to make, for the data are meager and are given in a variety of ways.

Sudry (33, p. 136) reports from the Thau Lagoon, in southern France (near Cette), 0.47 per cent of sulfur in the muds of the crique de l'Angle. That is a sheltered portion of the Lagoon. But in the center, more open part, the sulfur content of the muds drops to 0.35 to 0.40 per cent. The total carbon varies from 2 to 3 per cent.

According to Sudry's method of analysis, these figures represent not only sulfur in any sulfides that may have been present, but sulfate as well, including the sulfates of sea water that was entrapped when the samples were dried. Also included is sulfur combined in the more or less stable minerals that may have been present.

H. B. Moore (25) has made a study of an estuarine basin, the Firth of Clyde, in southwestern Scotland. His data, recalculated to total carbon from the nitrogen figures, give a range of 0.5 to 5.0 per cent, with the lower values characteristic of the deeper portions of the mud. Correlation of depth of sample and carbon content is not obvious.

To Vardabasso (36) we are indebted for quantitative data pertaining to muds of the Black Sea which were given some attention, but only qualitatively, by Andrussov (1). Again, total sulfur is given, amounting to 6.8 per cent. The amount of organic matter is uncertain, since Vardabasso states that loss on ignition, which represents CO_2 of carbonates, combined H_2O, and organic matter, amounts to 7.36 per cent, and these were not determined separately.

Trask (35, p. 37) reports higher or-

ganic content in the depressions than on the ridges of the Channel Islands region, California. No data on sulfide content are given. The possibility is suggested that the Channel Islands basins are areas in which the water is comparatively quiet and perhaps favorable for the concentration of planktonic and terrigenous organic debris. This hypothesis is supported by the fact that there

> fine-grained deposits accumulate in the basins and coarse-grained sediments form on the ridges and divides (p. 29).

This condition is apparently not analogous to the situation in Monterey Bay where gravels belonging to the present age of deposition may be found in the deepest portions of the submarine channels.

In brief, then, the iron sulfide content of a marine black mud is seldom over 2 per cent, and the organic carbon content is seldom over 5 per cent.

The Alkaline Anaerobic Environment.—The alkaline environment in the sulfide mud is of considerable interest. A case in point arises in a discussion of the environment of Pennsylvanian times by R. C. Moore (26, p. 465):

> An acid and toxic environment is indicated by the nature of the plant débris, the presence of sulfides. . . .

If the statement is based on analogy with present conditions, it is in error. The syngenetic monosulfides bear no evidence for acid conditions. The anaerobic phase of the sulfur cycle is carried on in an alkaline milieu.

It is a generally recognized fact that anaerobic decomposition tends to raise the pH.[2] L. G. M. Baas-Becking, in a written communication to the writer, noted that

> the organisms (of the sulfuretum) occurred exclusively in alkaline waters, pH 7.6-8.6, either fresh water, sea water, or brine.

Moreover, the ferrous iron is soluble when the pH is less than 6.5; hence, in any case, the mud could only be very feebly acid and yet leave the hydrotroilite undecomposed.

The following series of pH readings of black mud from Monterey Bay shows that the milieu is alkaline and that the stability of the sulfide precipitate is maintained:

Station	*Depth of water Meters*	pH
67-B	0.5	8.6
15	76	8.7
90	88	8.2
103	265	8.4
131	492	8.1

Similar data are furnished by Bruce (6, p. 559) who found the black layer of certain beach sands to range from 7.9 to 8.1.

Nadson (30), in one of the first careful works on the black mud and its micro-organic community, also says that the mud shows an alkaline reaction and, incidentally, is very rich in carbonates.

It is only upon oxidation that the milieu becomes acid. But then sulfide formation ceases and the entire community of organisms which promote the sulfur cycle in the anaerobic phase

[2] pH is a symbol used to represent the concentration of free hydrogen ions, hence the acidity, of a solution. Seven is taken as the neutral point. Figures of 7 to 14 indicate progressive alkalinity; 7 to 0 indicate progressive acidity. Further details may be found in (9; 24; 34, p. 448).

is destroyed, at least for the time being. In this regard Bruce (*op. cit.*) states:

> In all cases, the filtrate from the dark layers, originally clear, became opalescent on exposure to the air, and the pH fell.

The lower limit of his pH values is not stated, but the present writer has found the milieu to change from 8.8 to 6.2 when the mud is exposed to the air. Meehan and Becking (23) have noted a change from 7.6 to 6.8.

This shift, *which occurs on aeration,* is caused by the formation of organic as well as mineral acids, and is accompanied by the oxidation of the ferrous iron. This conversion may operate in several ways.

When the hydrogen sulfide that is generated is allowed to dissipate the following reaction may proceed to the right:

$$4FeS + O_2 + 10H_2O = 4Fe(OH)_3 + 4H_2S + \text{ENERGY}^3$$

or

$$4FeS + 9O_2 + 10H_2O = 4Fe(OH)_3 + 4H_2SO_4 + \text{ENERGY}$$

At the same time carbon dioxide, as well as organic acids, may be produced from the oxidation of organic matter. Hydrolysis of the carbon dioxide forms carbonic acid:

$$H_2O + CO_2 = H_2CO_3$$

The reaction of the carbonic acid with any available ferrous iron forms iron carbonate:

$$FeS + H_2CO_3 = FeCO_3 + H_2S$$

The formation of this particular compound is especially important, for it will be mentioned later that the ferrous carbonate provides a source of energy, upon oxidation, for certain bacteria.

The essential points are that the sulfuretum is dominantly alkaline, that there is a *momentary acidification* on aeration, and that, in the case of sea water buffered to a pH of 8.0 to 8.3, there is a steep gradient in acidity between any local acid area and the surrounding sea water.

These remarks have a bearing on Sudry's experiments (33, p. 136) on the black sediments. His experiments consisted in placing various muds in both fresh and salt water in tightly stoppered flasks. Formalin was then added, presumably to kill any living organisms. The formalin, however, was apparently neutralized by the protein present, for he obtained after a time a black color in the sediments. The color was attributed to:

> l'action réductrice des matieres organiques sur les sulphates de l'eau de mer (p. 137).

He also obtained in the flasks "la vase superficielle oxydee" (*op. cit.*), and found that shells placed in the mud had either disappeared or were badly decomposed. This he attributed only to "l'acide sulfurique qui attaque le carbonate de chaux" (p. 138), the sulfuric acid being formed by the oxidation of the ferrous sulfide.

As to the first inference, it has been pointed out by Bastin (2) that there is no evidence for considering dead organic matter capable of reducing sulfates at ordinary temperatures. Moreover, it is apparent that insufficient formalin was added to eliminate bacterial

[3] The amount of energy liberated is not essential here, so is not given. Whenever stated it is given in calories.

activity and that although the flasks were tightly stoppered, oxygen was at first present in them. Otherwise the superficial oxidation layer would not have formed.

The fact that oxygen was available permits a consideration of reactions which would operate under aerobic and then anaerobic conditions. Under the former, the development of sulfate by oxidation is possible. Then, after oxygen depletion, anaerobic sulfate reduction in the sulfuretum follows. Thus the complete cycle is carried out. The shell decomposition may also be aided by the formation of nitric acid under aerobic conditions, the acid being generated from the oxidation of ammonia compounds.

The above remarks are presented to show that biochemical reactions which take place during and after the formation of the black mud are extremely complex, and statements relating to them require careful consideration.

THE BROWN LAYER IN SEDIMENTS

The superficial layer of brown to reddish-brown color which usually overlies black mud contains a variable percentage of ferric hydroxide. The content is usually lowest near the top of the sediment and increases with proximity to the sulfide region lying immediately below. The statement is a generalization, however, and does not apply in some cases. The following data give some idea of the iron content of this ferric hydroxide layer. The analyses refer to a point approximately one centimeter above the contact between the black, FeS, line and the brown layer itself.

Station	*Depth of water Meters*	*Fe Per cent*
34	105	0.2
104	306	0.2
90	88	0.2
16	37	0.3
103	265	0.8

There is apparently no correlation with depth or with the iron content of the underlying black mud (see previous table).

The formation of this brown layer brings into the picture the study of a group of micro-organisms different from those discussed already. The change from black mud to brown mud signifies, in this discussion, an oxidation of the iron from the ferrous to the ferric condition. Such an oxidation liberates energy which, under the proper conditions, may be utilized by a group of micro-organisms. The scheme is shown in figure 1.

This assemblage of "iron organisms" which lives in the brown layer is somewhat complex. Harder (15) has divided it into the following groups:

1. Autotrophic, or those to which the oxidation of ferrous iron provides a source of energy for the assimilation of CO_2.

2. Heterotrophic, or those which precipitate ferric hydroxide or basic ferric salts from organic iron salt solutions (such as citrate) by the assimilation of the organic acid radical.

3. Facultative autotrophic, or those which deposit ferric hydroxide when either organic or inorganic iron salts are present and which do not need ferrous bicarbonate for metabolism. The inorganic iron salts, however, can not be used as sources of energy.

There is some doubt as to the cor-

rectness of these divisions. Such a question lies outside the scope of this paper, but it should be pointed out that Meehan and Becking (23) have suggested that several of the "thread bacteria" mentioned by Harder are probably identical. Moreover, it is possible that these thread bacteria are only the gelatinous stalks of a protozoon. (Compare, however, 27.)

It seems, however, according to Waksman that:

> Certain bacteria are able to utilize the energy obtained from the oxidation of certain iron compounds and live autotrophically. . . . The process supplies the organism with the necessary energy for the chemosynthetic assimilation of CO_2:
>
> $$2FeCO_3 + 3H_2O + \tfrac{1}{2}O_2 = 2Fe(OH)_3 + 2CO_2 + 29.8 \text{ cal.} \ldots$$
>
> Other ferrous salts will not take the place of the carbonate. Much organic matter impairs growth and may finally stop it altogether (37, p. 402).

It must be emphasized that the micro-organisms are *not instrumental* in oxidizing the iron. Rather, they are present to utilize the energy which is liberated by the oxidation process, and the process proceeds unaided under aerobic conditions. In other words, the change from ferrous to ferric iron liberates a certain amount of thermal energy which a particular group of micro-organisms can utilize. It should be added that the energy released by the oxidation of manganese can also be used by the group.

From a geological point of view, then, they are important as the localizers of ferric iron precipitation. That is, by their forming sheaths of iron hydroxide around the cells, these organisms build a matte. It is more or less gelatinous at first, but during the passage of time becomes indurated.

Harder and Chamberlin (16), Ellis (11), and Gruner (14) have discussed adequately the possible roles the iron organisms have played in the formation of some of the most important sedimentary iron ores. Comparatively little work has been done on the part these organisms may play in forming ocherous concretions. Nothing original is presented in the present paper, but the opportunity is taken to call attention to some observations made in Russia.

Concretion Formation.—There is the possibility that the activities of the iron organisms do not assume much importance in an open basin such as Monterey Bay, principally because the sedimentation is fairly rapid and water currents are relatively variable and strong. But when the geobiological processes become instrumental in the formation of concretionary objects, a thorough understanding of them is of considerable value.

The "iron organisms" are probably important factors in forming ocherous concretions, and it is very probable that physico-chemical processes (rhythmic precipitation, colloidal influence, etc.) may play but a minor part.

In an open basin, wave and current action may be too strong to allow the ferric hydroxide of the iron organisms mat to be more than ephemeral. That is, water movement may not permit the ferric hydroxide to remain in the bottom sediment after the enclosed organisms have either been destroyed or have formed other sheaths. But in

a quiet basin it is possible that the deposit would remain undisturbed for a long time. In fact, Butkewitsch (7) has recently described from the White Sea, Russia, ocherous concretions which have evidently formed *in situ*. He shows definitely the presence and importance of the iron organisms in the concretions and comes to the conclusion that:

> Die Tätigkeit der spezifischen Eisen und Mangan ablagernden Organismen beschränkt sich wahrscheinlich nur auf eine bestimmte Zone in der Oberschicht des Meeresgrundes, wo sich diese Tätigkeit in der Bildung von Belagen, Anschwemmungen, Zwischenschichten, einzelner Konkretionen aussert (p. 73).

The concretions described by Butkewitsch average 2 by 5 centimeters in size. They are essentially limonite-cemented sands which have started from a central nucleus and the ringed structures that are evident are due to differences in iron concentration. Structures similar to these have usually been interpreted as examples of the Liesegang phenomenon (22, pp. 122-155) or of the results of the operation of certain physico-chemical forces outlined by Schade (32).

In any event, it is evident that the geobiological history of a concretion deserve as much attention as the hypothecated ideas concerning the rôle of inorganic agencies in its formation.

SUMMARY

A complex community of micro-organisms characterize the black marine muds and a number of biochemical reactions are involved in the formation of these muds. The areas of hydrotroilite accumulation are dominantly alkaline and their development is the normal thing to expect where organic matter and sulfate are available.

The "iron-manganese organisms" must be considered in the formation of limonitic sediments, and it is probable that certain ocherous concretions are due essentially to the activities of micro-organisms rather than to inorganic reactions alone.

In conclusion the writer wishes to express his thanks to Dr. C. B. Van Niel for many suggestions made during the course of the investigation.

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CALCIUM CARBONATE IN BEACH SANDS

GERALD R. MacCARTHY
University of North Carolina

ABSTRACT

The calcium carbonate content of 73 beach and 9 wind-blown sands was estimated by means of leaching with hydrochloric acid. The results of these analyses are tabulated and it is pointed out that north of northern North Carolina calcareous beach sands are the exception, while south of this point they are the rule. A striking difference in respect to carbonate content between sands collected on the ocean and on the sound side of sand bars is also noted.

In connection with recent investigations on the general subject of beach sands, the present writer has studied the acid-soluble material contained in several dozen samples of beach and dune sands. Some generalized statements regarding his findings have appeared elsewhere[1] but in view of the recent interest in this subject as expressed in recent papers[2, 3] it seems advisable to report the results of these analyses in more detail.

No formal chemical analyses were made; the samples were simply washed on the filter with tap water, dried to a constant weight at 110°C., leached with cold dilute (1:4) HCl, washed again, redried and again weighed, the percentage loss in weight being taken as representing the $CaCO_3$ content of the sample. That no great errors were introduced by using this simple procedure is indicated by qualitative tests made on the acid filtrate from several samples: these filtrates contained practically nothing in the way of bases but calcium. Martens[4] reports a sample of beach sand from Flagler Beach as containing 55.95 per cent $CaCO_3$ as determined by formal analysis, while the present writer found 57.63 per cent of this material by the far simpler method of leaching. Since the two samples concerned were collected by different persons and at different times, the agreement is surprisingly close.

The following table gives the percentages of $CaCO_3$ found in beach sands from various localities by the present writer. Most of the samples studied had been collected by the U. S. Coast Guard, and such samples are marked

[1] MacCarthy, Gerald R., Beach sands of the Atlantic Coast: *Science*, new ser., vol. 73, pp. 284-285, 1931. Coastal sands of the eastern United States: *Am. Jour. Sci.*, vol. 22, pp. 35-50, 1931. The $CaCO_3$ content of certain beach sands: *Jour. Elisha Mitchell Sci. Soc.*, vol. 47, p. 11, 1932.

[2] Raymond, Percy E., and Stetson, H. C., A calcareous beach on the Coast of Maine: *Jour. of Sedimentary Petrology*, vol. 2, pp. 51-62, 1932.

[3] Raymond, Percy, E., and Hutchins, Forbes, A calcareous beach at John O'Groats, Scotland: *Jour. of Sedimentary Petrology*, vol. 2, pp. 63-67, 1932.

[4] Martens, James H. C., The beaches of Florida: *Florida Geol. Survey, 21st-22nd Ann. Rept.*, p. 82, 1931.

TABLE I.—*The $CaCO_3$ content of certain beach sands as determined by leaching washed and oven-dried sands with cold dilute HCl.*[5]

No.	Location	Percentage loss on leaching
67*	Amagansett, New York	0.16
71*	¾ mi. S. of Southampton, New York	0.08
74*	½ mi. S. of Quogue, New York	0.12
76*	2½ miles S.W. Speonk Point, W. Hampton Beach, N. Y.	0.17
80*	4½ miles S. Patchague, N. Y.	0.15
83*	Fire Island Beach, ½ mi. W. of F. I. Light, N. Y.	0.15
86*	Jones Beach, 2 mi. W. of East End, N. Y.	0.09
89*	Long Beach, 1½ miles W. of Jones Inlet, N. Y.	0.15
92*	Rockaway Beach, 2½ miles E. of Rockaway Point, N. Y.	0.23
97*	Bay side Sandy Hook, ½ mi. S. of Point, N. J.	0.60
103*	Avon, N. J.	0.60
110*	Island Beach, 1½ miles S. of Seaside Park	0.09
116*	Middle of Long Beach, Ship Bottom, N. J.	0.27
123*	Absecon Light, Atlantic City	0.12
128*	Ludlam Beach, Strathmere, N. J.	0.51
134*	Five Mile Beach, Wildwood, N. J.	0.22
137*	Cape May Point, Cape May, N. J.	0.22
140*	Cape Henlopen, Lewes, Del.	0.11
144*	1½ miles N. Fenwick Island Light, Shelbyville, Del	0.10
147*	10 miles S. Ocean City, Md.	0.12
151*	Wallops Beach, Virginia	0.31
153*	South End of Cedar Island, Wachapreague, Va.	0.50
155*	Near S. End Hog Island, Broadwater, Va.	0.35
156*	Near S. End Cobb Island, Oyster, Va.	0.30
157*	Smith Island, ¾ mi. Cape Charles Light, Townsend, Va.	0.43
161*	Cape Henry, Va	0.44
163*	10 miles S. of Cape Henry Light	0.00
164*	On Beach at North Bay, Virginia Beach, Va.	0.11
164-B		0.21
166*	8¼ miles N. of Currituck Beach Light	0.19
166-B		0.25
168*	¼ mile S.E. of Currituck Beach Light, N. C.	0.32
168-B		0.91
169*	5⅝ miles S. of Currituck Beach Light, N. C.	0.31
169-B		0.18
170*	11 miles S. of Currituck Beach Light, N. C.	5.84
170-B		0.16
171*	17⅜ miles S. of Currituck Beach Light, N. C.	2.12
171-B		0.17
172*	Kitty Hawk, N. C.	5.08
172-B		0.17
173*	1⅜ miles S.E. of Kill Devil Hills, N. C.	2.53
173-B		0.19
175*	Bodie Island, N. C.	0.62
175-B		0.15
176*	1⅜ miles S. of Oregon Inlet, N. C	1.58
176-B		0.10
177*	5¼ miles S. of Oregon Inlet	1.03
177-B		0.29
179*	4½ miles S. of New Inlet, Rodanthe, N. C.	1.30
179-B		0.14
180*	17¼ miles N. of Cape Hatteras Light, Salvo, N. C.	0.99
180-B		0.10
181*	10⅝ miles N. of Cape Hatteras Light	0.79
181-B		0.47

[5] Numbers marked * are numbers of coast guard stations. Numbers followed by –B are from the SOUND (not ocean) beaches.

TABLE I. (*Continued*)

No.	Location	Percentage loss on leaching
182*	6 miles N. of Cape Hatteras Light	2.19
182-B		0.11
183*	1 mile S. of Cape Hatteras Light	4.09
183-B		0.18
184*	7 miles W. by S. of Cape Hatteras Light	14.09
184-B		0.48
185*	3½ miles E. of Hatteras Inlet, Hatteras, N. C.	3.70
185-B		0.14
186*	Ocracoke Island, 1 mi. E. of Hatteras Inlet	12.73
186-B		2.87
187*	Ocracoke, ½ mile N. of Light	8.09
187-B		0.23
188*	5 miles W.S.W. Ocracoke Light, Portsmouth, N. C.	6.87
188-B		0.38
189*	Core Bank, Atlantic, N. C.	13.57
189-B		0.37
190*	1½ miles S. of Cape Lookout Light, Harkers Island, N. C.	17.52
190-B		10.78
191*	¼ mi. N.W. of Fort Macon, Beaufort, N. C.	7.75
191a	Morehead City, N. C.	2.41
191b	Broad Creek, near Newport, N. C.	4.26
192*	Bogue Inlet, Swansboro, N. C.	1.82
192-B		0.58
192x	South Point New River Inlet, N. C.	3.72
192a	Wrightsville Beach, N. C.	10.43
192b	Carolina Beach, N. C.	4.78
192c	Fort Fisher, N. C.	3.31
193*	Cape Fear, midway between Cape Fear & Bald Head Lights	3.02
193-B		1.90
194*	Oak Island, 1 mi. West Ft. Caswell, N. C.	1.43
194-B		1.44
195	Holden Beach (near Supply), N. C.	2.23
195a	2 mi. N. of Seaside, N. C.	1.51
195b	Cherry Grove Beach, S. C.	1.99
195c	8½ miles N. of Myrtle Beach, S. C.	1.64
195d	Myrtle Beach, S. C.	2.33
195e	Floral Beach, S. C. (10 miles S. of Myrtle Beach)	3.80
195f	Magnolia Beach, Brookgreen, S. C.	2.60
195g	Pawley's Island, S. C. (Near Georgetown)	4.10
196*	Moultrieville, S. C.	1.27
196-B		1.28
202*	Flagler Beach, Florida	57.63
204*	12 miles N.N.W. of Cape Canaveral, Florida	16.63
204-B		0.10
206*	3 miles N. of Fort Pierce Inlet, St. Lucie, Florida	48.36
206-B		21.05
207*	2½ miles N. of St. Lucie Point, Salerno, Florida	43.54
207-B		8.24

by a star. Samples whose identifying number is followed by a –B were obtained from the inner or sound beach of an off-shore bar.

As has already been reported,[6] the average beach north of northern North Carolina seems to contain very little calcareous material, while southward from this vicinity the ocean beaches all

[6] MacCarthy, G. R., Coastal sands of the eastern United States: *Am. Jour. Sci.*, vol. 22, pp. 46-47, 1931.

contain considerable amounts of $CaCO_3$. In almost every case samples taken from the inner or sound side of an off-shore bar are relatively low in calcareous material and in many cases are practically devoid of it. Also a marked tendency has been found for those sands which are coarser than their immediate neighbors along the coast to contain more of these calcareous materials.

TABLE II.—*Acid-soluble content of wind-blown sands, in per cent.*

Sample	Per cent
Crest of dune, Dune Park, Indiana	2.83 (E)
Lee base of dune. Dune Park, Indiana	2.89 (E)
Windward base of dune. Dune Park, Indiana	2.55 (E)
Crest of large dune. Nag's Head, N. C.	0.04
Mojave Desert. Near Baker, California	0.58
Dune d'Ain Lefra. Oran, Algeria.	0.75
Escalante Desert. Near Toquerville, Utah	0.33
Rajputana Desert. Hasanpur, (24°15′:72°35′) India	4.70 (E)
Rajputana Desert. Jujani, (25°4′: 72°14′), India	1.13 (E)

In Table II above, the acid-soluble content of several wind-blown sands, as determined by the writer, is given for purposes of comparison. Only those marked (E) showed noticeable effervescence.

That the northern beaches rich in $CaCO_3$ reported on by Raymond, Stetson, and Hutchins are not unique is indicated by the fact that 42.2 per cent $CaCO_3$ has been reported in beach sands and 32.1 to 34.2 per cent in wind-blown sands from the North Coast of Sutherland.[7]

Several problems connected with the calcareous content of various types of sand deposits are evidently in need of solution, e.g., the cause of the sudden change in content at a point along the northern portion of the North Carolina coast, the reasons for occasional calcareous beaches in northern latitudes, the great difference in composition of ocean and sound beaches, the organisms from which calcareous fragments are derived, etc. An excellent start toward the solution of some of these problems has been made by Raymond, Stetson, and Hutchins in the papers referred to above, but a more general attack should be started in the near future. It is not the purpose of this paper to discuss any questions of origin or controlling factors, but simply to place on record a series of observations, which, in the opinion of the writer, should be of interest to all sedimentary petrologists.

[7] Barrett, W. H., The grading of dune sand by wind: *Geol. Mag.*, vol. 67, p. 161, 1930.

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THE PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE SEDIMENTS OF LAKE MENDOTA, A FRESH WATER LAKE OF WISCONSIN

W. H. TWENHOFEL

ABSTRACT

The paper gives physical and chemical analyses of the sediments of Lake Mendota. The sediments over the bottom are very fine-grained and are composed of 60 to 80 per cent carbonate, mostly calcium, about 20 per cent silica, and small percentages of alumina and iron oxide. When first deposited the sediments are black soupy oozes rich in organic matter. Elimination of the organic matter by micro-organisms changes these to light-colored marls. These deposits are made in depths to a maximum of 80 feet.

GENERAL CONSIDERATIONS

In this article there are described the physical and chemical characteristics of the sediments covering the basin of Lake Mendota, a fresh water lake adjacent to the city of Madison, Wisconsin. The studies were made by the writer assisted by several of his students and have been continued from time to time as conditions permitted beginning about 1927. As the writer's limitations in the progress of the work have about been reached it seems best to place the results on record. Further advance must be made in the realm of micro-biology and very encouraging progress is being obtained under the direction of Professors E. B. Fred and Elizabeth McCoy and Mr. F. T. Williams of the Department of Agricultural Bacteriology of the University of Wisconsin.

The work done by the writer or under his direction has been made possible through a grant from the Bache Fund of the National Academy of Sciences. This was used for the construction of apparatus to obtain the samples.

DESCRIPTION OF LAKE MENDOTA AND SURROUNDING TERRITORY

Lake Mendota is a fresh water lake situated on the north side of the city of Madison, Wisconsin. It has an area of 15 to 16 square miles, is 3 to 4 miles wide at its greatest width, and is about 6 miles long. The greatest depth is about 80 feet.

Prior to the advent of the Pleistocene ice sheets the basin in which the lake lies was a part of the valley of a stream flowing in an easterly direction. Deposition of morainic material made by the retreating ice sheet formed a dam and brought the lake into being. The bottom of the depression originally seems to have been over two hundred feet below the present surface of the lake, but this has been filled to the extent of over one hundred feet.

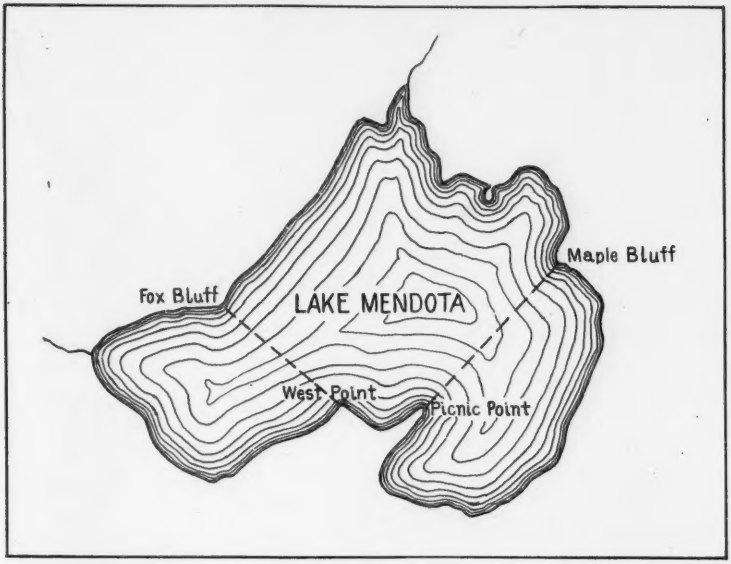


FIG. 1. Outline of Lake Mendota showing the shape of the lake and the positions of the traverses.

The bed rocks about the lake consist of Cambrian and Ordovician limestones and sandstones, and over these lie glacial drift and loess. The rocks at lake level and for 60 to 70 feet above are quartz and glauconitic sandstones with some dolomite on the tops of some of the highest cliffs. The higher hills about the lake are capped with Ordovician dolomite. The region around the lake has a relief exceeding 100 feet, and the surface is generally rolling, affording a ready run-off to precipitation. The geologic section with brief explanations is as follows:

ORDOVICIAN

Platteville dolomite. Up to about 20 feet thick on top of a few hills to the northeast.

St. Peter sandstone. Variable thickness. Probably 50 feet within a distance of a couple of miles to the northwest and northeast.

Oneota dolomite. There is an estimated thickness of a maximum of about 100 feet within a mile of the lake.

CAMBRIAN

Madison sandstone. The "quarry sandstone." There is some controversy respecting the limits of this formation. The writer's opinion is leaning to the view that only that part quarried for building stone should be assigned to the Madison, and the loose friable sandstones below should be considered a part of the underlying member. On this basis the Madison sandstone would have a thickness of not more than 12 feet.

Trempealeau or St. Lawrence formation.

Jordan-Norwalk sandstone. Seen at Farwell's Point and in all the quarries be-

low the Madison. Probably 20 to 25 feet thick.

Lodi shales with dolomite cap. Seen at Farwell's Point, Maple Bluff, excavation for the Congregational Church, Pheasant Branch, etc. About 12 feet.

Mendota dolomite. Seen at Farwell's Point, Maple Bluff, Pheasant Branch, and numerous other places about the lake. Ulrich attempted to assign the Mendota dolomite to a position between the Madison and Jordan sandstones. No field evidence exists for this assignment as it has never been seen in that position. The evidence in the writer's and in Mr. G. O. Raasch's possession shows very clearly that its position is in the Trempealeau formation. The matter will be treated in detail in a paper in progress of preparation by Mr. G. O. Raasch and the writer. The Mendota dolomite forms the summits of several cliffs on the shores of the lake.

Franconia formation. This formation extends in most exposures on the lake shore to the water's edge. There is a maximum thickness of about 100 feet.

Eau Claire formation.

Dresbach sandstone. This sandstone underlies the lake.

In addition to contributions from several very strong springs, two small streams flow into Lake Mendota. One of these is on the west end and is known as Pheasant Branch. This rises for the most part in the area of an extinct lake about the village of Middleton, flows thence with a considerable gradient through a recessional moraine to a low swampy area over which it leaves essentially all of any visibly suspended sediment, and thence enters Lake Mendota as clear water. The second stream is known as Yahara River. This is on the north side of the lake, rises in the hills to the north, thence flows through a swampy area, and finally enters Lake Mendota free of much suspended sediment. The springs entering the lake bring little other than clear water. All entering waters seem to carry considerable dissolved matter, chiefly carbonates derived from solution of the limestones, glacial tills, and loess through which they flow. Some contributions of inorganic matter in the form of finely divided material are received from erosion of the shores, and no doubt there are considerable contributions from the atmosphere.

As is characteristic of most lakes of temperate climates, Lake Mendota has overturn of its waters twice each year, one immediately preceding the freezing of its surface in early winter and the second in the spring about the time the ice leaves the lake. These two overturns bring oxygen to the bottom, but it is thought that this is soon exhausted by organisms of the bottom waters and decomposition of organic matter in the soupy oozes covering the bottom.

THE SEDIMENTS OVER THE BOTTOM OF LAKE MENDOTA

The materials over those parts of the bottom of Lake Mendota near the shores are sands, muds, and organic sediments, the proportions varying from place to place. Present information indicates that the bottom away from the shores and beneath a black ooze is floored to an undetermined depth by a marly deposit which on a dry basis contains around 60 to 80 per cent of carbonate of which all except a minor part is calcium carbonate. The materials on the immediate bottom of the lake are very black soupy oozes a foot or more in thickness,

which at the top gradually pass into the waters of the lake and at the bottom into fine marls which are also black, the change to the marls seeming to be fairly abrupt. The firm deposits gradually change color, becoming first dark-gray and finally very light-gray, the change in color taking place in a depth that does not exceed 8 feet. These firm marls have a water content ranging around 70 to 80 per cent. Small thread-like worms seem to constitute the chief forms of macroscopic life in the soupy oozes, and no macroscopic forms seem to be present in the firm marls. No stratification of any kind was observed in any of the samples taken. It is thought that fish may stir up the muds during those times that the bottom of the lake is provided with oxygen and thus to some extent destroy the lamination that otherwise might make its appearance as the soupy oozes became compacted.

METHODS OF OBTAINING SAMPLES

The samples were obtained in two ways and on two traverses across the lake as is indicated in the diagram of Figure 1. The soupy oozes covering the firm muds of the bottom were obtained by means of a clam-shell or Ekman sampler. The marls below the oozes were sampled by means of a brass tube 3 inches in diameter on the outside and 6 feet long. This tube is provided with a steel base that screws into it and with a heavy top in which there is a valve. Supported above the top is a brass cylinder about 3 inches in diameter and 1.5 inches thick. A steel rod about 20 inches long extends upward from this cylinder to a smaller cylinder, and on this rod is a lead cylinder with a hole through the middle. This lead cylinder weighs about 25 pounds and serves as a hammer to drive the tube into the mud or to drive it out after it has been driven in. Inside the brass tube is placed a tin cylinder open along one side. The entire apparatus is lowered to the bottom of the lake by means of a windlass, and then the lead hammer, which is attached to a rope distinct from that used to lower and raise the brass tube, is used to drive the tube as far as possible into the mud, the depth penetrated being measured by the length of rope released from the windlass. In soft muds it is known that the steel point has been driven as much as 8 feet below the bottom of the oozes. On being brought to the surface the base is removed from the brass tube, the tin cylinder extracted, a new one placed therein, and the operation may be repeated.[1] The tin cylinder fills to about half its length, but it is thought that the filling represents a section to the depth penetrated. The opening along one side of the cylinder renders the core therein accessible. No commitment is made as to the depth from which the samples come, it merely being stated that each sample analyzed comes from the top or the bottom of a core.

The samples were collected along two lines across the lake, one from Picnic Point to Maple Bluff, and a second from West Point to Fox Bluff. The

[1] The instrument was in part suggested by one devised in the University of California and by the work of Drs. E. A. Birge and C. Juday who used a device for driving a thermometer into the bottom.

samples were obtained through the ice during the winter, the first being collected in 1927-1928 and others during succeeding winters to that of 1931-1932.

C. S. Black in 1929 published analyses of the sediments in several Wisconsin lakes and also some from Alaska, the samples having been obtained by means of an Ekman dredge. One sample was taken from Lake Mendota. This appears to represent the bottom oozes. Mr. Black also made analyses of material from the top, middle, and bottom of a core taken by the present writer from the middle of Lake Mendota on the line from Picnic Point to Maple Bluff, and these analyses are given in an unpublished thesis prepared by him. They agree in essentials with those given on the following pages

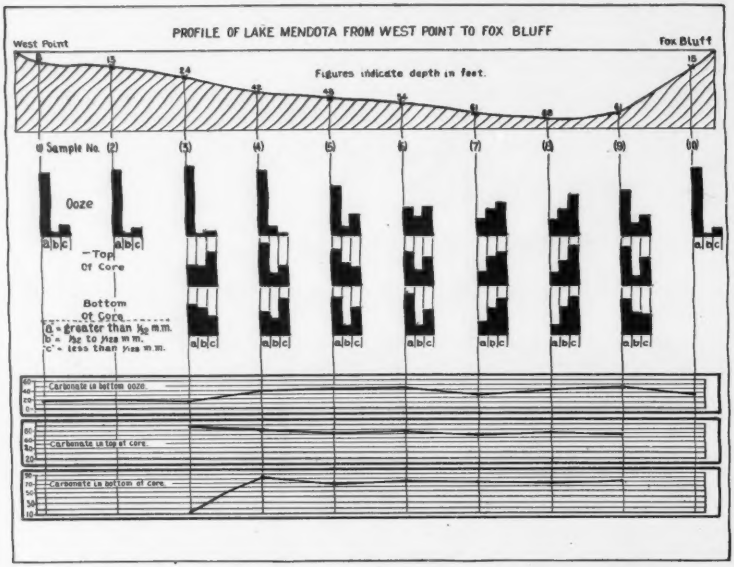

PROFILE OF LAKE MENDOTA FROM WEST POINT TO FOX BLUFF
West Point
Fox Bluff
Figures indicate depth in feet.
Sample No.
Ooze
Top Of Core
Bottom Of Core
a = greater than 1/50 m.m.
b = 1/50 to 1/250 m.m.
c = less than 1/250 m.m.
Carbonate in bottom ooze
Carbonate in top of core
Carbonate in bottom of core

FIG. 2. Histograms of samples taken at the depths and places indicated on a line from West Point to Fox Bluff. At the base are three curves giving the carbonate content at the depths and places indicated.

PREVIOUS STUDIES OF THE SEDIMENTS OF LAKE MENDOTA

Essentially no work has been done on the sediments of Lake Mendota. In 1917 Doctor W. O. Hotchkiss made some preliminary studies, and he republished an analysis of the muds which had previously been published by Birge and Juday. Hotchkiss did not continue the studies.[2]

[2] Hotchkiss, W. O., A method of measuring post-glacial time: *Geol. Soc. America, Bull.*, vol. 28, pp. 138-141, 1917; Birge, E. A., and C. Juday, *Wisconsin Geol. and Nat. Hist. Survey, Bull.* 22, p. 172, 1911.

except that the alumina is slightly higher.[3]

ANALYSES OF LAKE MENDOTA MUDS

The analyses are both physical and chemical. The samples obtained on the line from West Point to Fox Bluff were collected by Mr. R. G. Schuehle during the winter of 1930 and 1931, and the physical analyses were made by Mr. Schuehle under the direction of the writer. As the cores in the sampler are never as long as the sampler the exact depths beneath the bottom from which they came is not known; hence the designation top and bottom, the top being that depth beneath the soupy ooze at which the sediments become firm and the bottom being around 6 to 8 feet. All the materials were graded into three divisions by settling: (*a*) consisting of materials greater than

[3] Black, C. S., Chemical analyses of lake deposits: *Wisconsin Acad. Sci., Trans.*, vol. 24, pp. 127-133, 1929.

TABLE I. *Analyses of Lake Mendota Muds.*

Sample Number	Distance in feet from West Point	Grades	Ooze (Per cent)	Top (Per cent)	Bottom (Per cent)	Depth in feet
1	100	*a*	85.20			8
		b	1.30			
		c	13.40			
2	300	*a*	90.40			13
		b	0.60			
		c	9.00			
3	500	*a*	94.70	27.20	41.55	24
		b	1.90	26.05	35.85	
		c	3.40	46.75	22.60	
4	2000	*a*	88.60	58.40	29.20	42
		b	10.90	14.70	20.60	
		c	0.50	23.90	50.20	
5	3500	*a*	63.10	49.80	52.40	48
		b	8.20	28.30	12.40	
		c	28.70	21.90	35.20	
6	5000	*a*	38.40	45.20	56.50	54
		b	22.60	16.70	12.10	
		c	39.00	38.10	31.40	
7	6500	*a*	20.20	15.10	16.70	61
		b	35.70	39.10	34.40	
		c	44.10	45.80	48.90	
8	8000	*a*	18.20	13.20	12.90	68
		b	35.60	31.10	35.31	
		c	53.80	55.70	51.80	
9	10,000, 1800 ft. from Fox Bluff	*a*	60.90	52.30	47.90	61
		b	14.00	11.30	26.50	
		c	25.10	36.40	25.60	
10	11,500, 300 ft. from Fox Bluff	*a*	90.40			15
		b	0.40			
		c	9.20			

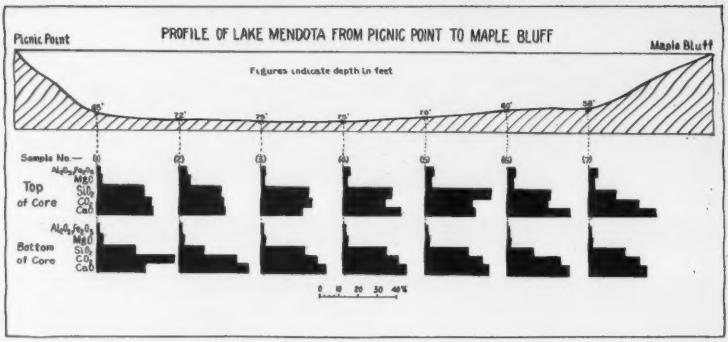


FIG. 3. Profile of Lake Mendota from Picnic Point to Maple Bluff. Depths of water are indicated in feet on the top ends of vertical lines at the bases of which are graphs giving the chemical composition of samples taken at the places and depths indicated. The upper part of each graph gives the analysis of the top part of a core and the lower part the analysis of the bottom of the same core.

1/32 mm. in diameter and most being less than 1/16 mm., (*b*) with diameters between 1/32 mm. and 1/128 mm., and (*c*) consisting of particles of which the diameters are less than 1/128 mm. It is appreciated that the classification can be little more than approximate (Fig. 2). The data are given in Table I.

Core samples were not obtained in the stations close to the shore as the cylindrical sampler could not be driven into the mud.

TABLE II.—*Carbonate content of Lake Mendota muds, in per cent.*

Sample	Ooze	Top of Core	Bottom of Core
1	18.50		
2	18.50		
3	14.30	87.90	12.80
4	39.20	80.00	83.80
5	41.50	70.90	66.40
6	44.00	75.00	73.20
7	28.60	66.40	70.30
8	39.10	71.50	69.00
9	45.20	67.20	71.00
10	25.20		

After drying at 105 C. to constant weight samples from the oozes and the top and bottom of the cores were determined for carbonate with the results shown in Table II and the curves of Figure 2.

It will be noticed that the oozes are low in carbonate compared to the materials of the cores. This arises from the high organic content of the oozes. In the core samples the organic matter has been largely eliminated. This is assumed to have been accomplished by micro-organisms.

Complete chemical analyses were made of core samples collected by Mr. L. L. Palmer on the line from Picnic Point to Maple Bluff. These analyses are given in Table III and Figure 3.

The calcium carbonate in the top muds is approximately 50 per cent calcite and about 50 per cent aragonite. These figures must not be given too much exactness as the percentages were determined by X-ray examination, and the error may be as much as

TABLE III. *Chemical analyses of Lake Mendota muds.*

Sample	1		2		3		4	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
SiO_2	24.08	19.70	21.86	12.95	24.72	22.74	24.68	22.57
CaO	28.65	24.87	23.57	36.27	21.77	33.02	29.96	32.41
CO_2	28.15	39.57	23.15	29.92	25.94	29.07	21.78	28.70
MgO	2.13	2.71	5.55	1.87	1.33	1.78	1.91	1.88
Al_2O_3	1.28	0.21	3.00	0.11	0.74	0.26	2.29	0.94
Fe_2O_3	0.79	0.75	0.65	0.72	0.79	0.57	0.79	0.57
Distance from Picnic Point in feet	1760		3520		5280		8040	
Depth of water in feet	65		72		75		75	

Sample	5		6		7	
	Top	Bottom	Top	Bottom	Top	Bottom
SiO_2	33.98	22.68	22.09	13.84	14.12	19.27
CaO	26.21	32.71	32.24	32.40	34.32	29.28
CO_2	24.66	29.67	21.33	27.99	26.68	26.99
MgO	2.61	1.69	3.13	1.93	2.65	1.89
Al_2O_3	3.27	0.82	2.87	0.31	3.69	0.59
Fe_2O_3	0.77	0.61	0.71	0.78	0.77	0.70
Distance from Picnic Point in feet	8800		10560		12320 (2640 ft. from Maple Bluff)	
Depth of water in feet	70		60		68	

20 per cent. The bottom muds are nearly all calcite.

Careful search was made in the muds for lamination and bedding, but none was found. This is thought to be due to the rather continuous deposition of the same kind of material and to later mixing of the bottom materials by organisms during those times when the bottom waters were provided with oxygen. Had any lamination been present in the materials of the first half dozen feet beneath the surface oozes it would seem that it should have shown in one or more of the numerous cores that have been collected, but not a single example was found.

The high carbonate content of the muds shows that the deposits will form a limestone with a low content of alumina and clay minerals but with a content of about one-fourth silica. A part of the silica is derived from diatoms, but a part seems to be finely divided quartz of allothogenic origin. The limestones will be massively bedded, with no or little lamination, extremely fine-grained, light-colored, finely crystalline, and, except for diatoms, almost devoid of fossil organisms.

GENERAL SUMMARY

The cores and bottom samples of the oozes show that sediments extremely

rich in organic matter and very black, through diagenetic processes, presumably brought about by micro-organisms, ultimately result in elimination of most of the organic matter in the transformation of the *raw calcareous sediments* into light-gray to white marls bearing little or no evidence of organic origin, and these, through lithification, will ultimately yield light-colored, fine-grained siliceous limestone containing little or no trace of organic origin. It should also be noted that these sediments are deposited in lake waters to a maximum depth of 80 feet and that there is the probability that they may have been deposited to a depth of over 100 feet as the marl is believed to extend to a depth of 35 feet beneath the present bottom.

Any inferences of conclusions drawn from studies of the sediments of Lake Mendota are applicable only to the sediments of lakes of the same character and with like surroundings. They can not be applied to the sediments of waters of other character. Studies similar to those described above and those in progress on the micro-organisms should be made of the sediments of lakes without overturn of water and of the sediments of the lakes and seas with sulphate and (or) saline waters. It may be suggested that in the sediments beneath sulphate waters there would be organic reduction of sulphates with formation of hydrogen sulphide and sulphuric acid, thus poisoning the waters with consequent large destruction of micro-organisms, and retention and preservation of much organic matter with consequent retention of dark colors in the sediments. Lakes without overturn might have the bottom sediments so poisoned by organic toxic products as to prevent microorganic elimination of organic matter.

This field of changes in the sediments of lakes and seas after deposition—the field of diagenesis—is essentially a virgin one in sedimentation. It is almost untouched, and it can not afford to be longer neglected. Previous studies of marine and lake sediments have almost exclusively been concerned with materials acquired from the immediate bottom of the water body. These sediments are *raw*, so to speak, and may be greatly different from what they will become after they have been buried beneath a half dozen feet of later sediments.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 3, NO. 2, PP. 77-82, FIGS. 1-2,
AUGUST, 1933

RIPPLE MARKS OF THE MERKLE DOLOMITE OF WESTERN TEXAS AND THEIR PALEOGEOGRAPHIC INTERPRETATION

LEROY T. PATTON
Texas Technological College, Lubbock, Texas

ABSTRACT

The extensive ripple marked surfaces of the Merkle dolomite show two main kinds of oscillation ripples, simple ripples and interference ripples. The latter are of the rectangular type. A study of the trends of the ripples show that they fall into two main groups, one with northeast-southwest trends, and the other with northwest-southeast trends. The prevailing type of interference ripples lends strength to the hypothesis of two main oscillation directions at right angles to each other as indicated by the two groups of trends of the simple ripples. Otherwise the interference ripples would be of the hexagonal type. The interpretation offered is that the northwest-southeast trends are the result of southwest planetary winds, and the northeast-southwest trends are the result of monsoon winds blowing toward the land mass of Llanoria.

The Merkle dolomite occurs near the top of the Clear Fork group of the Texas Permian. It was first described by Wrather.[1] It is named for the town of Merkle in the northwest corner of Taylor County. The main area of its outcrop is north of the Cretaceous overlap near the type section, through northern Taylor County, western Fisher County, and southern Stonewall County. This area is mainly in the Roby quadrangle of the U. S. Geological Survey.

In the east-central part of Stonewall County the Merkle dolomite disappears. Beede[2] believes that an unconformity cuts out the Merkle dolomite north of this location. Patton[3] has expressed the opinion that the disappearance of the dolomite in this direction may be due to a gradual lithologic change.

The study upon which this paper is based was made from near the Double Mountain Fork of the Brazos River south to the vicinity of Merkle.

The Merkle dolomite is a hard, white dolomite, varying in thickness from one to four feet. It is cut by bedding planes into layers of varying thickness. These bedding planes are invariably ripple marked surfaces.

All of the ripples are of the symmetrical type, that is the distance from the trough to the crest is the same on both sides of the crest, the crests are sharp and the hollows round and broad. No ripples of the asymmetrical type were observed.

Many of the ripples are interference ripples. Interference ripples result when an oscillation intersects a previous set of ripples and are of two main

[1] Wrather, W. E., Notes on the Texas Permian: *Southwestern Assoc. Petroleum Geol., Bull.*, vol. 1, pp. 93-96, 1917.

[2] Beede, J. W., and D. D. Christner, The San Angelo formation: *Texas Univ., Bull.* 2607, p. 12, 1926.

[3] Patton, L. T., The geology of Stonewall County: *Texas Univ., Bull.* 3027, pp. 15-17, 1930.

types, rectangular and hexagonal. In the rectangular type there are two sets of ridges which intersect each other at right angles. In the hexagonal type, to quote Bucher,[4] "the crests of the parallel ridges zigzag forming obtuse angles which in adjoining crests face in opposite directions connecting apices on alternate sides of each ridge."

TABLE I.—*Measurements of wave length and amplitude, and indices of ripples of the Merkle dolomite.*

Wave length in mm.	Amplitude in mm.	Ripple index
100	19	5.3
70	8	8.7
100	20	5.0
85	15	5.6
75	6	12.5
65	5	13.0
100	5	20.0
90	5	18.0
90	9	10.0
90	10	9.0
75	9	8.3
70	3	23.3
85	9	9.4
60	8	7.5
80	7	11.4
100	11	9.0
90	7	12.9
95	13	7.3
90	11	8.1
90	11	8.1
90	10	9.0
85	11	7.7
90	9	10.0
80	10	8.0
90	13	6.9
150	10	15.0
85	12	7.0
111	10	11.0
80	8	10.0
80	9	8.8
110	10	11.0
75	7	10.7
85	10	8.5
65	10	6.5
95	15	6.3
85	11	7.7
65	8	8.7
75	7	10.7
65	5	13.0
70	8	8.8

Average wave length 85.6 mm.
Average amplitude 9.5 mm.
Average ripple index 9.0

Many simple ripples are found, however, and their trend is easily determined. Even in the compound ripples one set of ripples is generally stronger than the other and the trend can be ascertained for one or both of them.

Measurements of the wave length and amplitude, and the ripple index for ripple marks studied in various parts of the area are given in Table I above. The ripple index is obtained by dividing the wave length by the amplitude.

A fairly comprehensive study was made of the trends of the ripple marks. The results of this study are shown in tabular form in Table II below.

The ripple marks occur throughout the whole vertical extent of the dolomite and observations recorded in the foregoing tables were taken on surfaces wherever exposed in place and include surfaces from the bottom to the top of the formation and represent, therefore, conditions which must have been fairly constant during the time of the deposition of the dolomite.

Interpretation of the Ripple Marks.—The fact that the ripples are of the symmetrical type and that no asymmetrical ripples were found anywhere in the formation shows that the ripples are all the result of oscillations and that neither tides nor wind drifts were effective.

The absence of tides indicate either an enclosed arm of the sea or lacustrine conditions. According to Bucher[5]

[4] Bucher, W. H., On ripples and related sedimentary surface forms and their paleogeographic interpretation: *Am. Jour. Sci.* (4), vol. 47, p. 190, 1919.

[5] *Op. cit.*, p. 243.

TABLE II.—*Trends of the ripple marks of the Merkle dolomite.*

Locality	Direction	Locality	Direction
1	S.56 W.	31	N.48 E.
2	N.45 W.	32	E.19 S.
3	N.29 W.	33	N.48 W.
4	S.34 E.	34	N.48 W.
5	N.42 W.	35	N.73 E.
6	N.48 W.	36	N.54 W.
7	N.79 W.	37	N.53 W.
8	S.51 W.	38	N.69 W.
9	N.52 W.	39	N.71 E.
10	N.19 W.	40	N.51 E.
11	N.52 W.	41	E.26 S.
12	S.35 W.	42	E.24 S.
13	S.54 W.	43	N.86 E.
14	N.70 W.	44	N.64 E.
15	S.26 W.	45	E.71 S.
16	N.50 W.	46	N.75 E.
17	N.35 W.	47	N.42 E.
18	N.49 W.	48	N.46 E.
19	N.69 W.	49	N.46 E.
20	S.62 W.	50	N.41 E.
21	N.41 W.	51	N.61 E.
22	S.54 W.	52	N.35 E.
23	N.46 W.	53	N.43 E.
24	S.43 W.	54	N.46 E.
25	N.47 W.	55	N.43 E.
26	N.64 W.	56	N.44 W.
27	S.57 W.	57	N.6 W.
28	N.49 W.	58	E.1 S.
29	N.30 E.	59	N.46 E.
30	N.49 W.	60	E.66 S.

the tides of Mediterranean seas are not sufficient to form current ripple marks. An epicontinental sea such as was in existence in this part of North America during the part of the Permian period in question would presumably not have sufficient tides to form ripple marks.

It has been shown by Bucher[6] that there is a direct relation between the size of the ripples and the depth of the water body, but that these relations vary within very large limits, and that very small ripples can be made in comparatively deep water by waves of large size and very small ripples can be produced in very shallow water by very small waves. Considering the nature of deposition of dolomite, however, it would seem probable that these ripples are the result of oscillations in water of moderate depth rather than small oscillations in very shallow water or large ones in comparatively deep water.

A study of the trends of the ripple marks brings out the fact that there seem to be two distinct groups of trends.

The trends were divided into six groups and plotted on six rays, each ray representing all of the trends 15 degrees on either side of it. The number of observations belonging to each group is shown graphically by the length of the rays and absolutely by

[6] *Idem*, pp. 188-189.

the number at the end of the ray. This is the method used by Bucher[7] in the study of the Brassfield formation.

An inspection of the plotted trends shows that the two general trends are NW-SE and NE-SW. This is even more strikingly brought out by taking

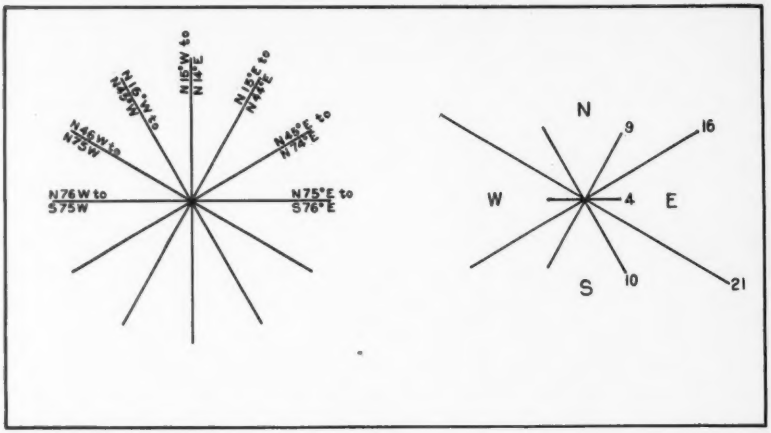


FIG. 1. Method of plotting the relative frequency of different trends of the ripples. Radii are drawn at intervals of 30 degrees and on these are plotted the number of observations of trends lying 15 degrees on either side. At the ends of the rays are given the actual number of observations.

the average of all the trends which apparently belong to the NW-SE group and the average of those belong to the NE-SW group. The average of the first group is N.54 W, and that of the second N.40 E., directions nearly at right angles to each other.

In this connection attention should be called to the relation of the interference ripples to the data just given. It has been pointed out that the interference ripples are the most numerous. They are, however, mostly of the rectangular rather than the hexagonal type. It has been proved experimentally that oscillations at angles with a pre-existing set of ripples do not result in any important change in the shape and orientation of the pre-existing set until a difference in trend of 45 degrees from the original set is reached. Between 45 and 90 degrees ripple marks of the hexagonal type are produced. When the direction of oscillation is 90 or nearly 90 degrees ripples of the rectangular type are formed.[8]

In light of the experimental evidence given above the fact that the prevailing type of interference ripples is the rectangular type is thought to be of significance, showing that there were two main oscillation directions at right angles to each other.

The winds which produced the ripples having a northwest-southeast

[7] *Op. cit.*, p. 265.

[8] Bucher, W. H., *op. cit.*, p. 192.

trend were either northeast or southwest winds. Of the two, southwest winds seem to be the more probable. It cannot of course be assumed that the atmospheric circulation of Permian time was exactly the same as that of the present. However, the causes of the general planetary circulation were operative in the Permian as well as in the present and this region might have been in a zone of prevailing southwesterly winds. If so this would account for the ripples with the northwest-southeast trend.

The second set of ripples, whose trend is northeast-southwest must have been caused by northwest or southeast winds. Of the two alternatives the first seems the more plausible. To the south and east of the Permian epicontinental sea lay the great land mass of Llanoria, which extended close to or within the boundaries of the present tropics. It is conceivable, therefore, that during part of the year the great land mass might become so highly heated that the monsoon winds caused by this heating would overcome the prevailing planetary winds and the monsoon winds would blow toward Llanoria. During the opposite season the monsoon winds might not be strong enough to overcome the planetary winds and these would prevail. Thus winds blowing from the southwest part of the year and from the northeast another part of the year would produce interference ripples of the rectangular type and simple ripples of two

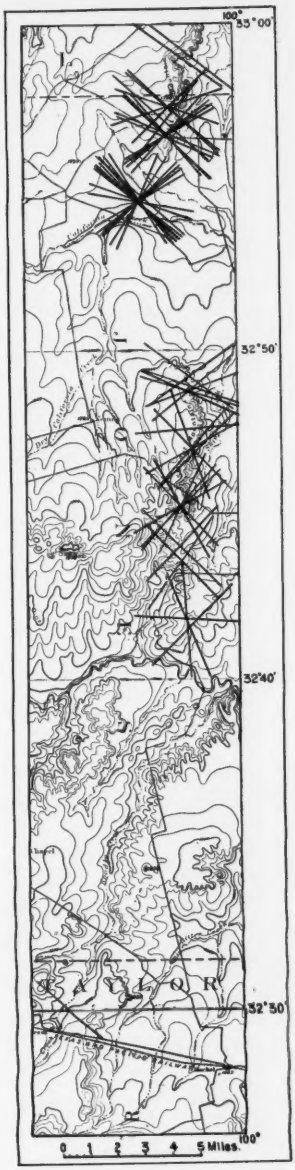


FIG. 2. Portions of topographic maps of Roby and Sweetwater quadrangles, Texas, upon which have been entered the trends of the ripple marks given in Table II. Trends are shown by black lines.

prevailing trends, namely, northeast-southwest and northwest-southeast.

The area over which the observations have been taken is sufficiently large to eliminate any local causes for cross rippling such as has been assigned by Kindle[9] as the cause of cross ripples.

The number of observations of the trend of the ripple marks is believed to be sufficient to eliminate any possibility of the concordance of trends in the two groups being due to chance. It is believed that the data regarding the trends are measurably strengthened by the fact that the cross rippling is of the rectangular type. Had the interference ripples been caused by winds blowing from many different directions the hexagonal type rather than the rectangular would be the rule.

It is believed, therefore, that the Merkle dolomite furnishes a paleogeographical record by which the climatic conditions in respect to atmospheric circulation during the time of its deposition may be determined. That this record is of course imperfect, and that the hypotheses based on it may be subject to modification is admitted; but it is believed that the record is sufficiently clear to warrant the tentative conclusions given above.

[9] Kindle, E. M., Recent and fossil ripple marks: *Canada Geol. Survey, Mus. Bull.* 25, 1917.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 3, NO. 2, PP. 83-91, FIGS. 1-2,
AUGUST, 1933

HEAVY MINERALS OF THE DRESBACH SANDSTONE OF WESTERN WISCONSIN

WALLACE L. WILGUS
University of Wisconsin

ABSTRACT

A study of the minerals of the Dresbach sandstone of western Wisconsin shows, with the exception of garnet, a relatively uniform and persistent suite of heavy minerals in all samples from outcrops. In order of abundance they consist of zircon, tourmaline, and the titanium minerals: ilmenite, leucoxene, and anatase. Garnet is common in sections along the Mississippi River, but rapidly decreases in abundance to the east, and disappears entirely from the sections east of Tunnel City and north of Leland. Rutile, brookite, staurolite, hornblende, and diopside are present only in one or two samples in very small amounts. In the well samples magnetite and pyrite predominate. The light minerals consist chiefly of quartz with some calcite, and an occasional grain of feldspar.

INTRODUCTION

The purpose of this paper is to describe the minerals composing the Dresbach sandstone and to show to what extent they may be used to differentiate this sandstone from the other Upper Cambrian sandstones of the upper Mississippi Valley. Suggestions are made respecting sources from which the minerals came.

Most of the samples were collected from outcrops (Fig. 1), but some were taken from deep well cuttings furnished through the courtesy of Mr. F. T. Thwaites. All samples were separated into heavy and light minerals following the method described by Reed[1] using tetrabromoethane (G.2.90-3.0). Both heavy and light minerals were examined microscopically with more attention being given the former.

The writer wishes to acknowledge the help of Dr. W. H. Twenhofel in planning the field work and directing the research, and the courtesy of Mr. F. T. Thwaites in furnishing the well samples. The suggestions and criticism of Mr. Gilbert Raasch have been very helpful.

The Dresbach sandstone is one of the formations of Upper Cambrian age, typically developed in the upper Mississippi Valley in western Wisconsin and eastern Minnesota. Its position in the Cambrian section is shown below.

CAMBRIAN SECTION OF WISCONSIN[2]

Trempealeau formation—(50-60 feet)
- Norwalk (Jordan?)
- Lodi
- St. Lawrence (Mendota)

Franconia formation—(100-170 feet)
- Mazomania
- Franconia (*sensu stricto*)
- Ironton

[1] Reed, R. D., Some methods for heavy mineral investigation: *Econ. Geology*, vol. 19, pp. 326-327, 1924.

[2] Raasch, G. O., and W. H. Twenhofel, Interview, January 20, 1933.

Eau Claire formation (700 ± feet)
Dresbach (100 ± feet)
Fossiliferous member generally known as Eau Claire
Mt. Simon

The Dresbach is a nonfossiliferous sandstone between the fossiliferous crops represent a maximum vertical range of 51 feet from the Ironton-Dresbach contact down, except for the Friendship Mound section which is undoubtedly much thicker. The deep well sections extend through a supposed maximum thickness of 100 feet.

FIG. 1. Map of Wisconsin indicating the distribution of sections of the Dresbach sandstone sampled for study.

member below and the Ironton member (locally absent) above. It is between 30 and 100 feet thick; the maximum thickness being found only in deep wells.[3] The samples collected from out-

With the exception of the work of

[3] Thwaites states that it is practically impossible to differentiate the sandstone formations in deep wells below the base of the Franconia, as the lithology of the sands is quite uniform throughout. He believes, however, that the Dresbach rarely exceeds 100 feet, a thickness based on the presence of a shaly horizon which occasionally exists at about this depth beneath the base of the Franconia. The deep well sections examined represent more than 100 feet beneath the base of the Franconia for the reason that no

Miss Eunice Peterson,[4] very little detailed work has been done on the Dresbach sandstone. According to the Wisconsin classification Miss Peterson's work deals with the combined Dresbach and underlying fossiliferous sandstones.

Recent studies of the Upper Cambrian sandstones have been made by Graham[5], Raasch[6], Pentland[7], Ockerman[8], and Twenhofel and Thwaites[9]. Twenhofel and Thwaites suggest that the Dresbach sandstone was accumulated in shallow water above wave base, or above water level. These conclusions were based upon the abundance of both wave and current ripple marks, the local presence of thin laminae of shale, the great development of cross lamination—some of which appears to be eolian—, the general absence of fossils, and the clean washing and excellent sorting of the sand in most of the beds.

MINERALS OF THE DRESBACH SANDSTONE

The light minerals of the Dresbach sandstone are quartz (94.3 per cent by weight), calcite and dolomite (5.7 per cent by weight), and an occasional grain of feldspar. The heavy minerals have been subdivided into allothogenic minerals including zircon, tourmaline, garnet, ilmenite, and magnetite; and authigenic minerals including leucoxene, anatase, rutile, brookite, and pyrite. The heavy minerals constitute but a small fraction of one per cent by weight of each sample.

LIGHT MINERALS

Quartz.—Two different varieties of quartz grains are present in the Dresbach sandstone. One variety consists of subangular to rounded, irregular grains with more or less glassy surfaces and containing inclusions giving a semi-turbid appearance; the other variety consists of well rounded, highly frosted grains. Particles of the latter variety are generally less common than the former and in some localities they may readily be distinguished on the basis of larger size.

ALLOTHOGENIC HEAVY MINERALS

The allothogenic heavy minerals include minerals of the source rock which, because of great stability, have withstood the physical and chemical processes of erosion.

Zircon.—The zircons are the most abundant of the allothogenic minerals, appearing as well rounded, colorless to light-yellow grains. Some are almost spherical, whereas others have an elongated biscuit-like shape. Only rarely do the zircons show the general outline of original crystalline form.

The surface of the zircons is usually dull; some of the grains are slightly frosted and under high magnification

definite lithological change could be found to suggest a base for the Dresbach.

[4] Peterson, E., The Dresbach formation of Minnesota: *Buffalo Soc. Nat. Sci.*, 14, pp. 6-49, 1929.

[5] Graham, W. A. P., A textural and petrographic study of the Cambrian sandstones of Minnesota: *Jour. Geology*, 38, pp. 696-716, 1930.

[6] Raasch, G. O., Unpublished material.

[7] Pentland, A. G., Heavy minerals of the Franconia-Mazomanie formation, Wisconsin: *Jour. of Sed. Petrology*, 1, pp. 23-36, 1931.

[8] Ockerman, J. W., Petrology of Madison and Jordan sandstone: *Jour. Geology*, 38, pp. 343-353, 1930.

[9] Twenhofel, W. H., and F. T. Thwaites, The Paleozoic section of the Tomah and Sparta quadrangles of Wisconsin: *Jour. Geology*, 27, pp. 614-633, 1919.

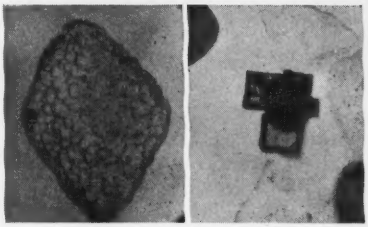
show a pitted surface. Liquid, mineral and clot-like inclusions are present in practically all grains. Zonal structure is present in some, and is always truncated by the rounded edges of the grain. Inclusions and zoning in zircons may be of some importance in determining the source rocks.

Tourmaline.—Tourmaline occurs persistently as well rounded grains which are usually somewhat larger than the average zircon. Only occasionally is there any indication of original crystalline habit. The brown, blue, green, and light yellow varieties are all found; grains of brown and green being most common. The grains contain liquid and mineral inclusions, but never in sufficient quantity to cloud them. The inclusions are usually bubbles and long needle-like particles without definite orientation.

Garnet.—The garnets that are present are extremely variable in shape and size, the shapes varying from irregularly angular to large well rounded grains. Colorless grains are most common. Inclusions are rarely present.

The surface characteristics of the garnets are striking and pitting, grooving, and etching are all present (Fig. 2a). Etching tends to give the surface and outline of the grains an irregular, hackly appearance, and practically all garnets in the sandstone, regardless of size, shape, or color, display this feature.

The etching of garnets has been considered by many petrographers as an unusual condition and one which has generally been misinterpreted. Mackie[10] noted the occurrence of etched garnets in the sandstones of Scotland and referred it to interstratal solution. Bramlette[11] made experimental studies on some crushed garnets by treating them with hydrofluoric acid and from his studies he concluded that etching is produced by acid or alkaline solutions circulating through the sediments subsequent to transportation and deposition, and that it is generally an authigenic change. Mackie further points out that sufficiently prolonged solution might entirely remove garnets from a sediment. It is possible that the total absence of garnets in the Dresbach at some localities may be explained in this way.



a *b*

FIG. 2. *a*, Highly magnified grain of garnet from Stoddard section showing characteristic etched surface (X 125). *b*, Leucoxene with anatase crystals projecting from it. The opaque round nucleus is leucoxene and the dark-bordered rectangular crystals are anatase; Stoddard section (X 125).

Ilmenite.—Ilmenite is most abundant and best displayed in the Point Bluff section (Fig. 1). It occurs as opaque, small pellet-like, extremely well-rounded grains. In reflected light

[10] Mackie, William, The principles that regulate the distribution of particles of heavy minerals in sedimentary rocks, as illustrated by the sandstones of northeast Scotland: *Trans. Edinburgh Geol. Soc.*, 11, Part II, pp. 147-148, 1923.

[11] Bramlette, M. N., Natural etching of detrital garnets: *Am. Mineralogist*, 14, pp. 336-337, 1929.

the grains have a purple-gray to reddish brown, submetallic luster. They are usually well polished and show signs of long transportation. Several of the grains in the lower part of the Point Bluff section have a blotchy appearance, which is probably a surficial expression of the early stages of alteration to leucoxene. As alteration continues the surface becomes porous and develops a white to yellowish-brown color.

McCartney[12] found that leucoxene is the most abundant heavy mineral in the Chester sandstones of Indiana, comprising at least 50 per cent and in some cases as high as 75 per cent of the heavy mineral crop. He found grains showing all transitions from black metallic ilmenite to leucoxene.

Magnetite.—Magnetite is much less common than ilmenite except in the deep well samples from Monroe and Chicago. It is present as irregular, subangular grains having a silver-gray to black metallic luster in reflected light. There are occasional small octohedral grains. It is not uncommon to find grains coated with limonite.

AUTHIGENIC HEAVY MINERALS

The most important authigenic minerals present in the Dresbach sandstone are the titaniferous minerals: leucoxene, anatase, brookite, and rutile, the first two being present in samples from nearly all exposed sections. Pyrite, another authigenic mineral, occurs abundantly in the well samples, but is entirely absent from outcrop samples.

[12] McCartney, G. C., A petrographic study of the Chester sandstones of Indiana: *Jour. Sed. Petrology*, 2, p. 84, 1931.

It has been suggested by McCartney[13] that surface water may be an important agent in developing titanium oxide minerals. He suggests that the circulating carbonated surface waters remove lime from leucoxene, resulting in the separation of TiO_2 as brookite and rutile (and probably anatase) with the SiO_2 becoming colloidal silica or crystallizing as quartz. The factors determining which of these three titanium minerals will be formed is not known, but the facts indicate that all three minerals apparently form under relatively similar conditions. McCartney found rutile and brookite with very little anatase in the Chester sandstones, whereas anatase with very little brookite and rutile is the rule in the Dresbach sandstone.

If circulating water is the chief agent for the formation of these titaniferous minerals, then the necessary conditions are quite favorable for their formation in the Dresbach sandstone. The Dresbach, as well as the other Upper Cambrian sandstones, are slightly inclined. The Dresbach is relatively porous, and in places, particularly in the vicinity of Mauston, is underlain by a few feet of shaly beds, thus producing a channel effect. Since the Dresbach outcrops at the surface over an extensive area there is ample opportunity for surface waters to gain access and subsequent circulation is easy.

Leucoxene.—Leucoxene with its authigenic derivatives is perhaps the most interesting of all secondary minerals found in the Dresbach sandstone. It is not abundant, but is sparingly present in all samples except those taken from

[13] McCartney, G. C., *op. cit.*, p. 87.

wells. Such a distribution strengthens the idea that surficial weathering conditions are important in its formation. It occurs as rounded opaque grains in transmitted light, but in reflected light it has a white to yellowish-brown color. The surface usually has a dull luster and is nearly always pitted. Many of these pits represent impressions left after the secondary anatase had been dislodged during preparation of the samples for study.

Anatase.—Anatase is the most common of the possible authigenic derivatives of leucoxene found in the Dresbach. Its authigenic origin seems indicated by its common occurrence as small, square, and rectangular crystals projecting from a central mass of leucoxene and there are many beautiful examples of anatase occurring in this manner (Fig. 2b). The crystalline outline is always present; pyramidal forms are sometimes found with striations parallel to the intersection of the prism. The color is usually straw-yellow to yellowish-brown. Tabular forms are frequently found alone and their sharp crystalline outlines seem to prove a secondary origin.

Rutile and Brookite.—These two titanium minerals occur only rarely in the Dresbach sandstones and they are always associated with leucoxene. Most grains are extremely small.

Pyrite.—Pyrite is found only in the samples from wells. It is all of secondary origin, as only whole and fractured euhedral grains occur. It has the characteristic brass-yellow color and luster in reflected light and frequently shows cubic faces which are striated.

Explanation of Table.—The accompanying table is a summary of the im-

TABLE I—*Summary of the percentages of the common heavy minerals found in each section.*

Mineral	Dresbach	Stoddard	La Crosse	Tunnel City	Leland	Wood Hill	Point Bluff	Friendship Mound	Chicago	Monroe
Zircon	C	A	A	A	D	D	A	D	P	P
Tourmaline	C	C	C	A	C	C	P	C	P	P
Pink	P	P							P	X
Garnet Col.	A	R	C	R	R				X	X
Leucoxene	R	R	R	R	R	R	R			
Ilmenite	X		C[a]	C		R	C			
Anatase	X			R				R		
Iron Oxide		C					C		D	(Coating grains)
Magnetite										D
Pyrite									A	P

[a] Includes ilmenite, magnetite and iron oxide, chiefly ilmenite.

portant heavy minerals occurring in the Dresbach sandstone at the different localities studied. Each letter represents the average percentage of the mineral present for the particular locality, in accordance with the key given below. The percentage of each mineral was determined by counting the grains.

	Key	
		Per cent
Flood	F	75-100
Dominant	D	50-75
Abundant	A	25-50
Common	C	10-25
Present	P	5-10
Rare	R	1-5
Trace	X	Less than 1

ORIGIN OF THE DRESBACH SANDSTONE

Conditions of Deposition.—The conditions under which the Dresbach sandstone was deposited are reflected in certain outstanding features, namely: (1) the total absence of fossils; (2) the presence of such structures as ripple marks, mud-cracks, and both wind and water cross lamination, and (3) the general uniformity in grain size, averaging 0.1 mm. to 0.4 mm. with the majority of the grains fairly well rounded and slightly frosted.

The above general characteristics seem to indicate that the deposition of the sediments composing the Dresbach sandstone took place in the upper portion of the neritic zone and in and above the littoral zone. Such environments seem to satisfy the facts better than any others.

It is suggested that the deposition of the Dresbach sandstone took place in a very shallow sea extending for many miles over a relatively flat, gently sloping surface and in which there was more or less continuous wave action, frequently milling over the rock particles contributed by streams. At times during low tide, large areas of the sea bottom are thought to have been exposed permitting drying of the finer sediments and the formation of mud cracks. Such an environment existing over a long period of time would be conducive to slow accumulation, with the result that any organic remains would be destroyed by wave action, or devoured by scavengers.

Source of Materials.—The physical characters of the allothogenic heavy minerals and the occurrence of only those minerals which are capable of withstanding one or more cycles of erosion, strongly suggest that the source of origin is not directly from an igneous terrane, but rather from the erosion and destruction of sedimentary formations.

In searching for sediments capable of furnishing the required minerals, the possibilities are limited to the large known areas of middle and upper Keweenawan sediments of the Lake Superior region, to sedimentary terranes once present but now removed, or to terranes concealed beneath later strata.

The upper Keweenawan clastics include sandstones, shales, and conglomerates.[14] No detailed mineral analysis of these sediments has been made,

[14] Van Hise, C. R., and C. K. Leith, Geology of the Lake Superior region: *U. S. Geol. Survey, Mon.* 52, pp. 413-414.

but quartz is very subordinate and in places the sediments are nearly quartzless. These conditions do not seem to favor the upper Keweenawan sediments as a source of the Dresbach sands.

Other important sedimentary formations of the Lake Superior region are the conglomerates and sandstones of the middle Keweenawan, which consist of materials from all varieties of basic, intermediate, and acidic rocks, but chiefly the latter which means that their dominant constituents are feldspar and quartz. These sediments might therefore, be considered as a possible but unlikely source for the Dresbach sands.

It is suggested that the sands may have been derived from sedimentary rocks which have been totally destroyed, or from rocks which at present are buried to the south, west, or east beneath the Paleozoics.

COMPARISON OF THE DRESBACH WITH OTHER UPPER CAMBRIAN FORMATIONS

Comparison of the Dresbach sandstone with other Upper Cambrian sandstones leads to interesting suggestions The following table shows the average percentages of the important heavy minerals from the Dresbach and three other Upper Cambrian sandstones. The figures given in the table represent the percentages of each mineral in the heavy mineral crop.

This table shows that the Dresbach sandstone may be distinguished from the Franconia-Mazomanie and the Madison-Jordan sandstones by the absence, or low percentage of garnets in the Dresbach as compared with the

TABLE II.—*A comparison of the heavy minerals of the Dresbach sandstone with those of three other Upper Cambrian sandstone formations, in per cent.*

		Dresbach	Eau Claire	Mazomanie—Franconia[15]	Madison—Jordan[16]
Zircon		25–50	10–25[a]	3 or 4[c]	10–25
Tourmaline		10–25	10–25	15[c]	5–10
Garnet	P.	1–5 or absent	absent	80[c]	75–100
	C.	1–5 or absent			
Ilmenite		5–10	50–75[b]		
Leucoxene		1–5	1–5		
Anatase		x	x		
Shell Fragments				Half of heavies	

[a] Average analysis of Dells section.
[b] Includes ilmenite, magnetite, and iron oxide.
[c] Percentages excluding shell fragments.

[15] Pentland, A. G., Heavy minerals of the Franconia-Mazomanie formation, Wisconsin: *Jour. of Sed. Petrology*, 1, pp. 23-36, 1931.

[16] Ockerman, J. W., Petrology of Madison and Jordan sandstone: *Jour. Geology*, 38, pp. 343-353, 1930.

other two sandstones, and by the relatively high percentage of zircon and tourmaline in the former as compared with the latter. The presence of the titaniferous minerals sparingly in all samples from Dresbach outcrops might also be cited as a distinctive feature of difference, as such minerals have not yet been reported as commonly occurring in the Upper Cambrian sandstones of Wisconsin that have been carefully studied.

Comparison of the minerals in the Dresbach sandstone with those from one section of the underlying fossiliferous sandstone, designated in the table Eau Claire, shows few differences. The notable one is the relative increase in abundance of the opaque minerals (ilmenite, magnetite and iron oxide) in the latter over the former. The zircon, tourmaline, and garnet are present in essentially the same amounts.

The results obtained from this study of the minerals of the Dresbach sandstone should be of some value in working out the Upper Cambrian stratigraphy of the Mississippi Valley. When detailed studies have been made of the heavy minerals of all Upper Cambrian formations of Wisconsin and Minnesota it may be possible to reach definite and acceptable conclusions with respect to the boundaries of the formations.

SUMMARY

The important facts or deductions derived from the study of the minerals of the Dresbach sandstone are as follows:

1. The principal heavy minerals are zircon, tourmaline, ilmenite, leucoxene, anatase, and locally garnet; with rutile, brookite, hornblende, staurolite, and diopside found only in one or two samples.

2. The occurrence of garnet in the Dresbach is variable, being entirely absent in sections in the vicinity of Mauston and Friendship, but appearing in increasing amounts up to 25 per cent in sections to the west along the Mississippi River.

3. The light minerals are chiefly quartz (approximately 95 per cent) and small amounts of calcite. Feldspar was found in a few samples at Dresbach, Minnesota.

4. On the basis of the heavy mineral suites it is possible to distinguish the Dresbach sandstone from the Franconia-Mazomanie and the Madison-Jordan sandstone units.

5. Sandstones below the Franconia are characterized chiefly by the absence or low percentage of garnet, whereas sandstones above the Franconia are characterized by a high content of garnet.

6. The physical characters of the heavy minerals, their great durability and the small variety suggest sedimentary terranes as the chief provenance for the materials of the Dresbach sandstone.

7. The evidence suggests that the Dresbach sands were deposited in environments belonging to the upper neritic and littoral zones and above the littoral zone.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 3, NO. 2, PP. 92-94, FIG. 1,
AUGUST, 1933

A MINERAL VARIATION SERIES OF BEACH SANDS FROM CEDAR POINT, OHIO

F. J. PETTIJOHN AND J. D. RIDGE
University of Chicago

ABSTRACT

The mineral composition and variations of a collected series of beach samples from Cedar Point, Ohio, on Lake Erie are described. The progressive decrease of certain minerals and increase of certain others in the direction of littoral current movement is attributed to selection on the basis of shape and density.

Beach sand samples were collected at about half mile intervals by Miss Charlotte Webster, of Elyria, Ohio, from Cedar Point, Ohio. Cedar Point is a spit, some seven miles from outer end to mainland connection, which extends from east to west nearly across the entrance to Sandusky Bay of Lake Erie. The mechanical and mineral composition of these sands was investigated by the writers. The mechanical analyses were described in an earlier number of this journal.[1] The present paper presents in brief form the results of the study of the minerals.

Two grade sizes (0.125–0.177 mm. and 0.177–0.250 mm.) were chosen for study. There was sufficient material in each of these grades in the 14 samples studied to make possible an easy separation into "lights" and "heavies" by means of bromoform (S.G. about 2.85). The acid-soluble carbonate had been removed with dilute HCl. A carefully quartered portion of the "heavies" was then mounted in Canada balsam for study under the microscope. The "lights" were not investigated.

About 300 grains in random fields in each slide were counted and the mineral composition expressed in per cent by number.

Each slide contained about 15 species of minerals. Minerals identified from the suite of samples were: garnet, hornblende, actinolite, tremolite, hypersthene, augite, diopside, epidote, titanite, zircon, staurolite, tourmaline, zoisite (?), magnetite, ilmenite, and leucoxene. The source for most of these is probably the glacial drift of the region. Of these minerals hornblende, garnet, hypersthene, and diopside occur in abundance in most samples. The others are present in small amounts excepting the various compound-polarizing altered grains which in a few samples make up a considerable percentage of the total.

Inspection of Fig. 1*B* will show the

[1] A textural variation series of beach sands from Cedar Point, Ohio: *Jour. of Sed. Petrology*, vol. 2, pp. 76-88, 1932.

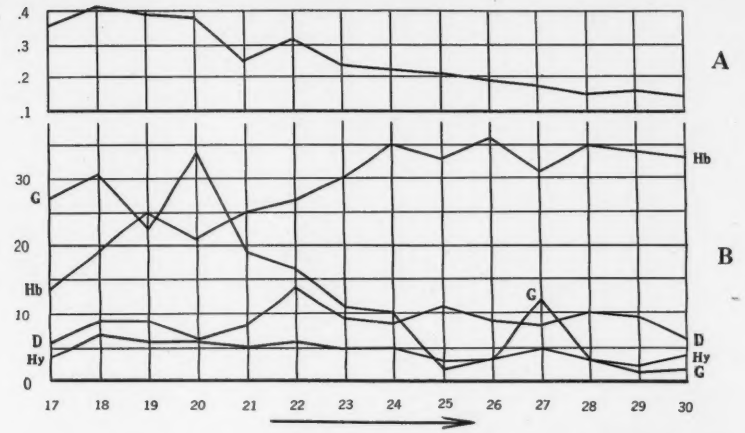


FIG. 1. *A*. Graph of weight median size (0.1-0.4 mm.) against distance. Samples 17-30, excepting 30, are spaced at half-mile intervals. *B*. Graph of per cent by number of garnet (*G*), hornblende (*Hb*), diopside (*D*), and hypersthene (*Hy*) grains in heavy separate of the 0.177-0.125 mm. grade size against distance (samples 17-30).

variations from sample to sample of the four principal minerals in the 0.177-0.125 mm. size. In both grade sizes garnet shows a marked decline (with fluctuations) from southeast to northwest, the direction of the shore drift. Hornblende shows a marked increase in the same direction. The behavior of diopside is less clear, but there is a slight increase in the direction of transit, while hypersthene shows a slight but definite decrease in direction of travel.

Both grade sizes were found to show essentially the same trends, but the minerals studied were not equally abundant in each grade. Hornblende was consistently more abundant in the finer size. Garnet, on the other hand, was generally more abundant in the coarser grade as were both diopside and hypersthene.

CONCLUSIONS

In the previous paper cited the decline in the median size was attributed mainly to selective sorting by the waves and littoral currents in such a way that the fine sizes out-ran the coarse in the direction of sand migration (see Fig. 1*A*). The change in mineral composition is attributed to the same causes. It cannot be that garnet is less stable than either diopside or hornblende but rather that it is left behind in preference to diopside or hornblende. The selection is perhaps due to both specific gravity and shape. The minerals selected, hornblende and diopside, probably have a specific gravity of about 3.0 to 3.3, whereas the specific gravity of hypersthene is perhaps about 3.4 or 3.5 and that of garnet still higher, perhaps 3.7 to 3.8 or higher. Moreover, the lower sphericity of the horn-

blende and diopside, due to the flat form of the cleavage fragments, stands in contrast to the more spherical (though angular)[2] garnets. Hypersthene has also a somewhat flat form but it has a higher specific gravity, as mentioned above, hence its very nearly neutral behavior.

To the eye, the minerals do not appear to become better rounded with transport. It is of interest to note that MacCarthy has recently[3] described an increase in "angularity" of the quartz of beach sands in the direction of travel. His "angularity," however, is really sphericity, or circularity as he expresses it for the cross section, and not roundness. He attributes this progression, rightly enough, to selective action. Since his grains were of the same mineral he did not have the factor of specific gravity to contend with.

[2] Sphericity and roundness are used in the manner defined by Wadell, Volume, shape, and roundness of rock particles: *Jour. Geology*, vol. 40, pp. 443-451, 1932.

[3] MacCarthy, G. R., The rounding of beach sands: *Am. Jour. Sci.* (5), vol. 25, pp. 205-224, 1933.

It was also noted in connection with the transportation of beach sands of southern Lake Michigan[4] that the hornblende increased in the direction of travel.

This tendency for grains of low sphericity to out-run grains of higher sphericity is characteristic of suspension sediments rather than traction sediments.[5] It appears, therefore, that suspension is the principal mode of travel for shore drift materials of the size studied and for the conditions prevalent at this locality. The differences in specific gravity as well as the differences in shape mentioned are factors in determining the selection described. Neither chemical stability nor resistance to abrasion seem to be factors in the changing mineral composition of this series.

[4] Pettijohn, F. J., Petrography of the beach sands of southern Lake Michigan: *Jour. Geology*, vol. 39, p. 454, 1931.

[5] Wadell, Hakon, Volume, shape, and roundness of rock particles: Thesis (Ph.D), University of Chicago, 1932. Wadell discusses this point at some length and sets up criteria for distinguishing between these types.

NOTES

CORRECTION OF AN ERROR IN "A HISTORY OF THE PRINCIPLES AND METHODS OF MECHANICAL ANALYSIS"

An inaccurate statement concerning the use of Stokes' law of settling velocities was included in the writer's paper under the above heading.[1] The error came to light during a review of the writer's original notes on the subject. It was stated that Schöne used Stokes' law when instead he used an equation which he had developed himself. Schöne's equation is

$$d = \frac{3\zeta v^2}{4g\,(s-1)},$$

where d is the diameter in mm., v is the settling velocity, s is the specific gravity of the particle, g is the acceleration due to gravity, and ζ is a coefficient.

It is suggested that a note be written on page 100 of the earlier paper, referring to the present correction.

W. C. KRUMBEIN
The University of Chicago

[1] *Jour. of Sed. Petrology*, vol. 2, pp. 100-101, 1932.

REVIEWS

GROUT, FRANK F., *Petrography and Petrology*. New York: McGraw-Hill Book Co., 1932, xvii + 522 p., 266 figs. Many tables—$4.50.

An interesting viewpoint of this moderately advanced text book and laboratory guide is the stress placed on interpretative petrology. The average textbook places the emphasis on the description of rocks leaving most of the interpretation of origin to be worked out by the student. The mature judgment of the author backed by his extensive field experience and laboratory study of igneous rocks makes his interpretative arguments convincing.

The book is divided into eight parts as follows: Introduction, 28 pages; The Petrography of Igneous Rocks, 114 pages; The Petrology of Igneous Rocks, 117 pages; The Petrography of Sedimentary Rocks, 45 pages; The Petrology of Sedimentary Rocks, 45 pages; The Petrography of Metamorphic Rocks, 25 pages; The Petrology of Metamorphic Rocks, 68 pages; Mineral Tables and Readings, 36 pages of tables and 25 pages of selected readings. A total of 231 pages is given to the discussion of igneous rocks, 90 pages to sedimentary rocks, 93 pages to metamorphic rocks and 89 pages to the introduction, tables, and selected readings. From the standpoint of the interpretation of earth history it is doubtful if the 22 per cent of the book devoted to sedimentary rocks is sufficient, but in view of the knowledge at hand the proportions of 55, 22 and 22 per cent for igneous, sedimentary and metamorphic rocks respectively are indicative of the progress which has been made in our studies.

The organization of the text, the excellence of the abundant illustrations, the apparent care exercised in the preparation and selection of diagrams and the completeness of the bibliographical references all aid in making this a valuable source book as well as a text book.

In this review only those parts of the book dealing with sedimentary rocks will be discussed. The fundamental thesis of the author that "the descriptive and systematic side of petrography is now so far advanced that few essential features of igneous rocks have escaped the careful petrographers"[1] can not be applied to sedimentary rocks. It is no doubt true that "reading the life history of a rock is a much higher achievement than a description and classification"[1] but there is much routine study and description

[1] Remarks quoted from Preface, page vii.

needed before interpretative theories that will stand the test of time can be properly devised for the sedimentary rocks. Already we have witnessed the downfall of a number of hypotheses devised to explain the origin of sediments. A brilliant imagination is an important part of a geologist's mental equipment but it should not shadow the need for finding facts from *a large number of examples* and the formation of a theory based on these facts. Deductive reasoning has had its fling and the student of sediments will sooner or later have to back up and use observed facts to explain the rocks instead of using a hypothetical origin and concluding a given rock is a type of the inferred process or environment.

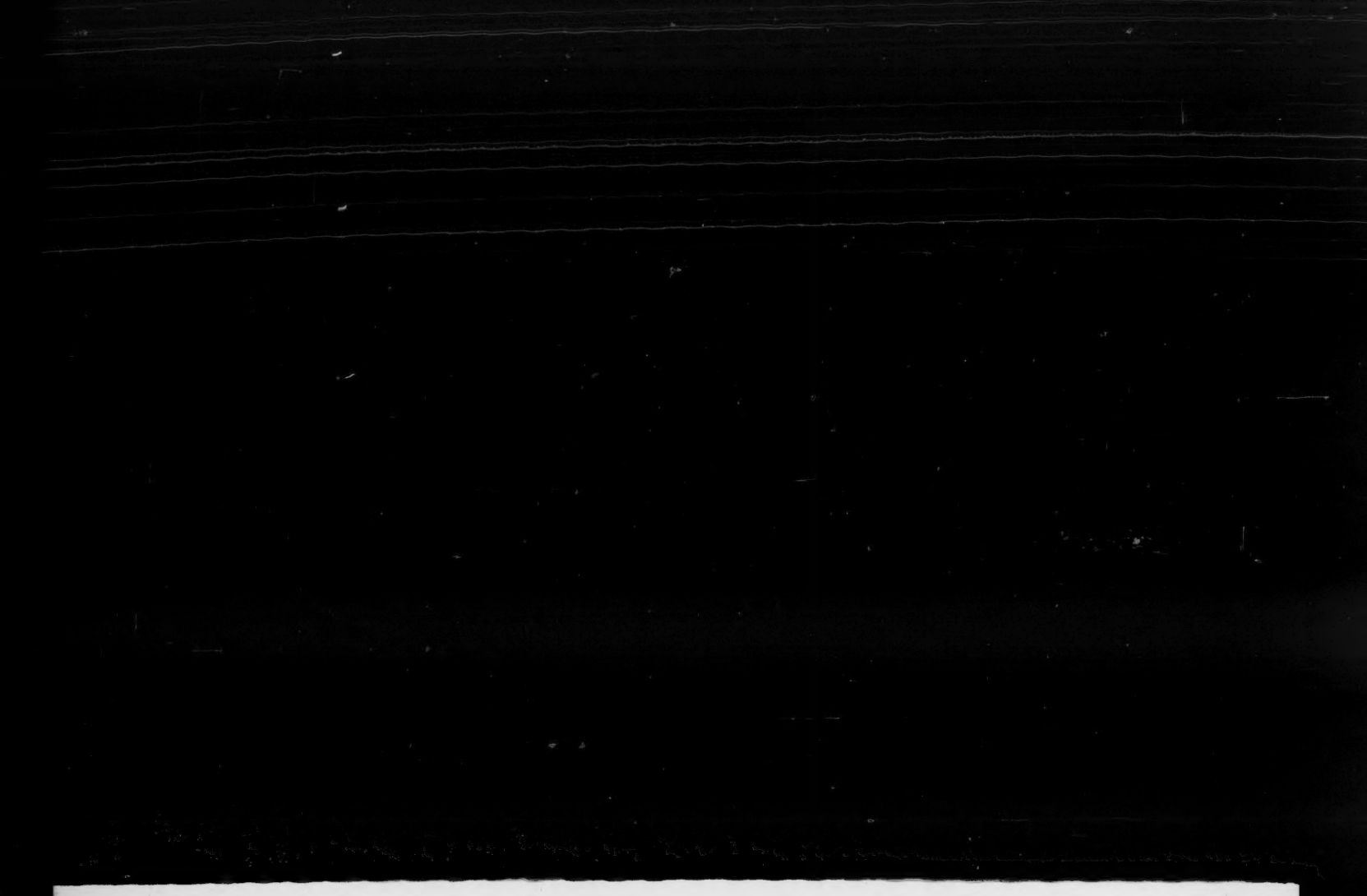
Part IV on the Petrography of Sedimentary Rocks defines sediments as "deposits of solid material (or material in transportation that may be deposited as solid) formed on the surface or in the outer crust of the earth under normal temperatures." General statements are made concerning lamination, textures and diagenesis, followed by a brief outline of methods used in the study of sediments. The discussion of the classification of sediments suggests the numerous difficulties encountered. Attention is called to some of the points in favor of the classification as proposed by Grabau and some of Grabau's rock terms are used in the discussions which follow. Grout groups all rocks under the principal clans of: (1) Clays and Shales, (2) Sands and other Mechanical Sediments (not clay and limestone), (3) Limestones, and (4) Miscellaneous Sedimentary Rocks. The last clan is discussed under heads of: Bedded Precipitates and "Evaporites" (other than limestone), Veins, Replacements, Residual Rocks, Organic Remains—not Limestones (which includes the various carbonaceous rocks, siliceous earths, limonite, etc.). The discussion of porosity, specific gravity, color, history, mineral association and economic materials is very brief in each case but thoughtful. For each clan the numerous varieties of rocks are listed with some of the principal characteristics and mineralogical varieties.

Taken as a whole Part IV is refreshing in that the organization is unique, most of the illustrations are good, and the text is easy to read. The reviewer is left with the feeling that the subject is too briefly discussed and there is a large amount of descriptive material omitted which would be helpful to the student of sediments.

Part V on the Petrology of Sedimentary Rocks discusses the sources of materials, weathering, transportation of sediments, deposition of sediments, equilibrium of constituents in sedimentation, diagenesis and other changes in sediments, alternative origins of some mineralogical types, sequences and cycles of sedimentation, and the interpretative petrography of sediments. Included in the discussion of several of the headings named above are lists of criteria which are helpful in the interpretation of sediments. The criteria suggesting a colloidal origin of minerals, the criteria of weathering, the criteria in weathered residues, suggesting nature of original rock, are well selected and suggestive of new thoughts. However, some of the other tabulations of criteria contain several hang-overs from doubtful *hypotheses*. The use of certain types of cross bedding, mud cracks, ripple-marks, shape and surface of grain has led too often to mistaken interpretations of the origin of sediments.

The list of selected readings is valuable to any worker interested in sediments. The book should be a worthy addition to any geologist's library.

A. C. TESTER

Iowa City, Iowa

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